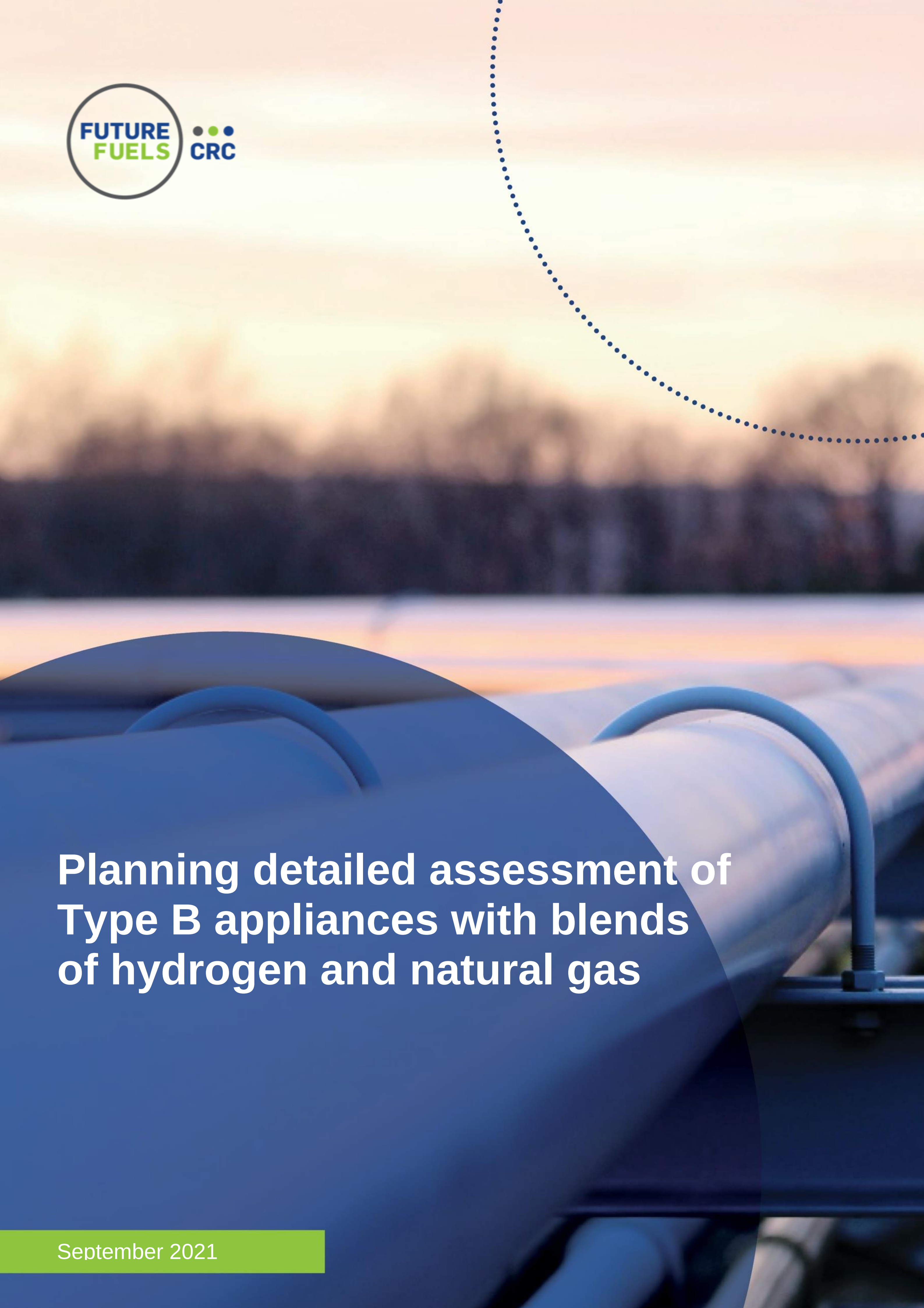


Planning detailed assessment of Type B appliances with blends of hydrogen and natural gas

September 2021

Project number: 1.4-06

Planning detailed assessment of Type B appliances with blends of hydrogen and natural gas

Authors:

Neil Smith

Alfonso Chinnici

Project team:

Peter Ashman, Paul Medwell, Neil Smith (University of Adelaide)

Yi Yang, Michael Brear (University of Melbourne)

Lead Industry Adviser/Team:

Troy Praag and Vikram Singh (AGIG)

Daniel Krosch (GPA)

Tristan Bodsworth (Jemena)

Marnie Foreman (ATCO)

Rilke de Vos (Advisian)

Deepank Gupta (Ausnet)

Kevin Dwyer (ESV)

David Oglesby (DELWP)

Australian Government
Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program

This work is funded by the Future Fuels CRC, supported through the Australian Government's Cooperative Research Centres Program. We gratefully acknowledge the cash and in-kind support from all our research, government and industry participants.

Important Disclaimer

Acknowledgement

This work is funded by the Future Fuels CRC, supported through the Australian Governments' Cooperative Research Centres Program. The cash and in-kind support from the industry participants is gratefully acknowledged.

In addition to the Industry partners on this project assistance was also given by the contacts from project Future Fuels Project RP1.4-02 and by staff of GasTrain, ATCO, ESV, Furnace Engineering, Techrite, Accumtherm and Honeywell.

Project Information	
Project number	RP1.4-06
Project title	Planning detailed assessment of Type B appliances
Research Program	RP1 Future Fuel Technologies, Systems and Markets
Milestone Report Number	2
Description	Final Report
Research Provider	University of Adelaide
Project Leader and Team	Peter Ashman, Paul Medwell, Neil Smith (University of Adelaide)
Industry Proponent and Advisor Team	Troy Praag and Vikram Singh (AGIG) Daniel Krosch (GPA) Tristan Bodsworth (Jemena) Marnie Foreman (ATCO) Kevin Dwyer (ESV) Rilke de Vos (Advisian) Deepank Gupta (Ausnet) David Oglesby (DELWP)
Related Commonwealth Schedule	Milestone RP1.4.3 “Solutions for new/modified industrial equipment delivered to allow for a broader range of fuel compositions” by detailed planning of testing and other assessments.
Project start/completion date	February 2021 / September 2021
IP Status	Confidential
Approved by	Troy Praag
Date of approval	October 2021

Contents

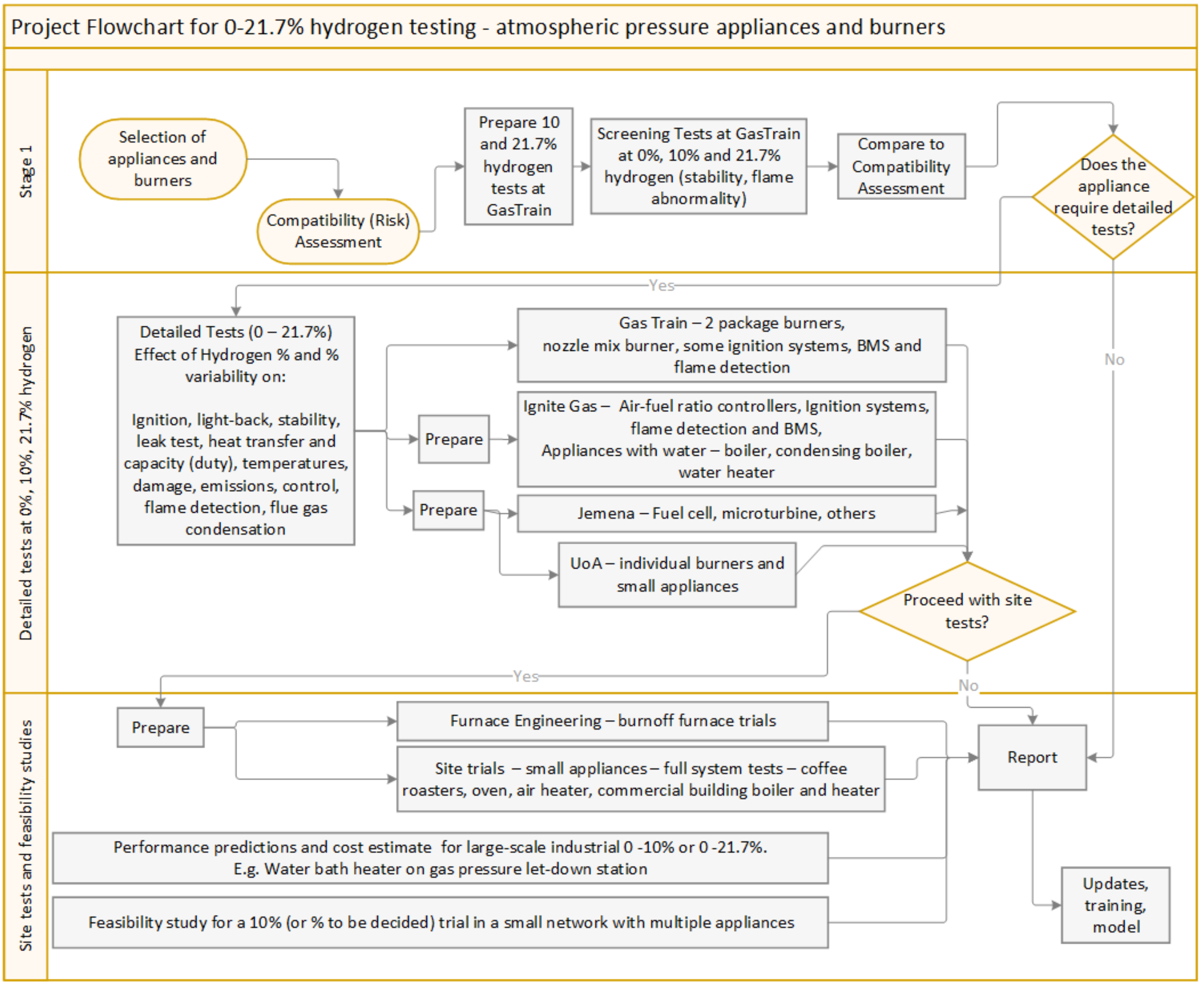
Summary of Report

This short project delivered a costed proposal (see the Appendix) for a larger FFCRC project, RP 1.4-08, to test and evaluate the addition of hydrogen to existing gas-fired Type B appliances. The proposal covers a representative range of atmospheric-pressure Type B appliances.

Injection of hydrogen into gas networks has commenced with various trials of up to 10 mol% hydrogen. Long-term targets for conversion of gas networks to 100% hydrogen have also been made. Hence, there is an industry need to:

a) Identify any compatibility issues with appliances, flame detection, burner management systems and valve train components with 10 mol% hydrogen in natural gas,
b) Determine upper limits for blending of hydrogen into natural gas for different types of Type B appliances,
c) Investigate costs and performance of appliances modified for 100% hydrogen, and
d) Recommend appropriate updates in appliance standards and training on updates.

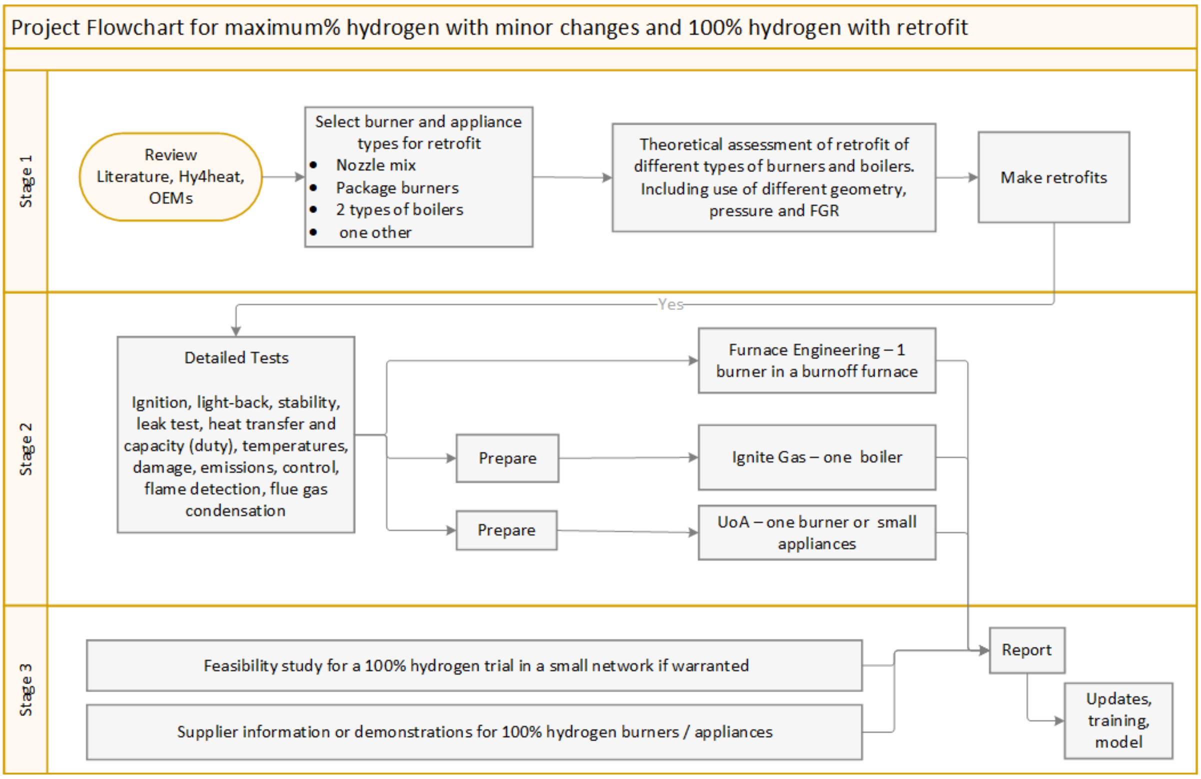
A survey of appliances found in pilot trial locations and more broadly was undertaken to the extent that is possible. The appliances were then categorised by burner type and so that future evaluation can be targeted at testing of burner types that are widely used in a variety of appliances. A range of burners, appliances and test facilities have been identified and included in the costed proposal, which can be summarised by the two flowcharts that follow. These flowcharts illustrate the approach to be used - including experimental testing and development, modelling of combustion and performance, and assessing feasibility of large-scale tests. The first flow-chart is for 10 mol% hydrogen blended into natural gas, and a limit gas of 21.7 mol% hydrogen, which was used in Type A testing to represent an upper level of excursion.



In Stage 1 the screening tests will be conducted using two different styles of package burners (these are the most common type of burner used in Type B equipment), and one each of the following burner types which covers as well as practical to the entire range used in Type B appliances:

- Nozzle mix burner
- Fully premixed non-radiant burners (for furnaces and Neon sign manufacture and pilot burners) – these have larger burner port areas than other types
- Air blast burner – uses air at about 7 kPa, compared to most others which are atmospheric.
- Atmospheric partial premixed venturi burner (many uses, e.g., ducted space heaters, pizza ovens, oil heaters, water heaters)
- Atmospheric partial premixed burner with induced draft fan (e.g., used in tumble dryers and pilot burners)
- Atmospheric natural draft partial premix porous ceramic radiant burner (e.g., used in space heating, paint drying, metal heat treatment)
- Atmospheric forced draft partial premix porous ceramic radiant burner
- Ribbon burners (partial premix and forced draft versions)
- Atmospheric partial premix with flame retention nozzle on end (used in galvanising)
- forced air partial premix infra-red burners (catalytic and non-catalytic) used in paint spray booths
- Forced draft nozzle mix (e.g., some galvanising line burners)
- Forced draft "high velocity" nozzle mix burner as used in immersion tube burners and some water bath heaters.
- Water bath heater – scaled down version of the inspirated premixed type with tall stack for natural draft
- Condensing boiler

The second flowchart illustrates the plan for testing and modelling with more than 21.7 mol% hydrogen blended into natural gas.



1. INTRODUCTION

This short project aims to assess options and deliver a costed proposal for a larger future project to test and evaluate the addition of hydrogen to existing gas-fired Type B appliances. The proposal covers a representative range of commercial and industrial end-users (but cannot cover all of them owing to the diversity and bespoke nature of Type B appliances). Other projects being undertaken in the FFCRC are focused on specific appliances and industries, which are not addressed by the current work. For example, PhD projects at University of Melbourne are investigating pressurised combustion appliances such as turbines and engines, and project RP1.4-03 at the University of Adelaide is investigating use of hydrogen in selected high-temperature industrial processes.

1.1 Type B appliances

Commercial and industrial gas users account for the majority of Australia's natural gas consumption. Type B appliances are typically used in these sectors. They are those for which a certification scheme does not exist (whereas mass produced appliances do have a certification scheme and are referred to as "Type A" appliances).

Examples of Type B appliances listed in AS 3814:2018 "Industrial and Commercial Gas Fired Appliances" include steam boilers, water heaters, air heaters, air curtains, process after-burners, incinerators and cremators, stationary engines and turbines, ovens, rotary process equipment, forced and induced draft burners. There are many other types of appliances and burners used in a range of industries. Most applications use natural gas for combustion which is used for either heating, power generation or motive power. Addition of hydrogen will have varying and, in some cases, unknown effects depending on blending ratio, appliance and burner design, and process requirements.

1.2 Australian hydrogen blending options and implications for end-user research

Targets to convert gas networks to 10 mol% hydrogen provide impetus to kick start a renewable hydrogen production industry in Australia. An allowance for variability in blend ratio can be assessed by testing with a range of compositions up to a limit. For example, 21.7 mol%[1] was used in FFCRC Type A appliance project RP1.4-01). The 21.7 mol% hydrogen blend with natural gas is also near the lower Wobbe Index limit allowed for natural gas[2], depending on the composition of the natural gas, which means it is also representative of a likely ceiling for blending in the short term. (Note that 10 mol% hydrogen is 3.4% by energy value, and 21.7 mol% hydrogen is 8.1% by energy value, based on higher heating values and assuming a typical natural gas higher heating value of 37.8 MJ/m^3).

It is also of interest to know the maximum hydrogen % in a blend with natural gas that various burner types and other equipment can handle with minimal changes to equipment; because some users or industrial precincts could also take a further step of blending with higher percentages of hydrogen if it is practical and cost effective.

---

[1]Type A natural gas appliances are tested with Nb limit gas (AS/NZS 5263.0), which is 13% hydrogen and 87% methane and has a Wobbe Index of 49.1 MJ/m^3. This Wobbe Index is typical of natural gas, because unlike natural gas, Nb gas doesn't have any traces of nitrogen or carbon dioxide. Hence the limit gas is designed for testing the effects of higher flame speed, lower ignition energy and lower stoichiometric air requirement that result from hydrogen addition, rather than testing a change in Wobbe Index.

For a new gas supply with 10 mol% hydrogen in natural gas, the new limit gas hydrogen content would be 10% + 13% of 90% = 21.7%. However, some tests in the UK and Germany have already been performed with 28 mol% or 30 mol%, so the limit gas used in our tests will also be somewhere in the range 0 – 30mol% hydrogen in natural gas, to be finalised during the screening tests. Screening tests will also assess any effects of rapid changes in composition within this range.

[2] The allowable Wobbe Index range for natural gas is 46-52 MJ/m^3 (AS 4564:2020). Pure methane has a Wobbe Index of 50.6 MJ/m^3 (calculated from the higher heating value of methane and using standard conditions of 15^{o}C and 101.325 kPa)

There may be no issues for the 10 mol% blend and the limit gas, but possible issues at these addition rates or higher injection rates need to be investigated and are the reasons that future work will include an assessment and testing program. Some of the potential issues are:

- Heat damage and higher NOx emissions due to higher flame temperatures (but the higher excess air with hydrogen blends may reduce flame temperatures and hence prevent damage and high NOx)
- Air/fuel ratio controllers, flame detectors, burner management systems may require adjustment
- Process performance – convection and radiant heat transfer will be affected, but the significance of the effects may be minor for 10 mol% hydrogen blends. Processes with recycled flue gas or using flue gas to preheat combustion air may be affected to a larger degree.

Targets to convert gas networks to 100% hydrogen have also been widely articulated both overseas and in Australia. For example, AGIG's 2020 Annual report included targets of a 100% hydrogen demonstration network by 2025, a 100% hydrogen subdivision by 2030 and a fully decarbonised network by 2040.

Hence, there is an industry need to:

a) Identify any compatibility issues with appliances, flame detection, burner management systems and valve train components with 10 vol% hydrogen in natural gas and with slightly higher levels that some pilot projects may push to, which can be accounted for by performing tests with a limit gas of 21.7 mole% hydrogen in natural gas.
b) Determine upper limits for blending of hydrogen into natural gas for different types of Type B appliances, with and without minor changes.
c) Determine which types of appliances can be modified for 100% hydrogen and provide a cost and performance comparison with emerging new appliances from manufacturers.
d) Have recommendations for updates in appliance standards and training on updates.

1.3 Test plans in other countries

A new European consortium (THyGA - Testing Hydrogen Admixtures for Gas Appliances), established in 2020, aims to assess both domestic and commercial appliances with blends of hydrogen and natural gas with low (<10 vol%), medium (10-30 vol%) and high (>60 vol%) hydrogen in the blends. They will use screening and segmentation before representative testing. Results will inform manufacturers and standards.

THyGA will test 100 appliances, including domestic and commercial, based on collaborative sourcing (Schaffert, et al., 2021). The types of appliances to be tested have not yet been revealed, but are expected to cover most types of commercial appliances, despite there being only two gas appliance manufacturing participants in THyGA, i.e.:

- BDR (Baxi) - who supply combined heat and power (CHP) to commercial buildings (e.g., hotels and hospitals), heaters and hot water (e.g., boilers up to 2.8MW), fuel cells, solar thermal hot water and also have developed a new hydrogen boiler.
- Electrolux - who mostly supply domestic appliances and commercial cookers

THyGA developed a testing protocol through an iterative process with many experts. It was noted that the % hydrogen addition will have a different effect depending on the Wobbe Index of the original natural gas it is blended with, so there was discussion about using both EU low and EU high natural gas for the tests. Their testing program will include some old, but mainly new appliances. Some of the tests are mandatory (agreed as part of THyGA funding). These are:

- safety, emissions, and efficiency
- operation and safety for different adjustments (light-back and CO emissions)

Other additional tests are:

- Extreme conditions – e.g., cold start, hot start, low air temperature
- Flame detector ionisation signal measurement
- Light back analysis
- Delayed ignition test

- Soundness (leakage)
- Qualitative response to quick variation in flow and shut-off
- Metal temperatures to check for overheating

A literature review by THyGA (Schaffert et al., 2020) showed it is likely that blending hydrogen into natural gas will result in no ignition delay, move the air fuel ratio and the flame stability range towards leaner conditions, reduce the power output or rating of the appliance slightly and reduce flame detector ionisation current. Overheating of components has not been observed and efficiency has been observed to increase in some studies and reduce in others.

THyGA is testing domestic and commercial appliances, but potentially not light industrial, so it is probable that some burner types used in Australian Type B appliances will not be tested. The Hy4Heat project (for conversion to 100% hydrogen appliances) deals with commercial and industrial appliances in two separate work packages. The demarcation between commercial (WP5) and industrial (WP6) was made at 1MW rating, and in addition, commercial heating was restricted to appliances supplied from network that operates below 7 bar. A review under the Hy4Heat WP5 (Ryan & Iliffe, 2020) lists only the following types of appliances as “commercial” in the UK:

- boilers
- radiant tube space heaters
- luminous ceramic radiant heaters
- direct and indirect fired warm air heaters and water heaters (storage, circulating and instantaneous)
- commercial catering appliances and tumble dryers in commercial laundries
- gas engine driven heat pumps.

THyGA may use a different demarcation to Hy4Heat, but if it is the same, then they will cover a narrower field of appliances than those designated as Type B in Australia. For example, oil heaters, dryers, ovens, furnaces, coffee roasters, paint spray booths, atmosphere generators, cremators and incinerators are Type B appliances found in Australian hydrogen injection pilot regions, but not on the “commercial” Hy4Heat list.

The Hy4Heat WP5 (i.e. <1MW rating) review found that there are wider variety of burner types than in domestic appliances, and normally performance needs to be more tightly controlled. Space heating accounts for 78% of gas use in the commercial sector in the UK, and the majority of that is consumed in boilers for “wet” space heating options. Boilers are also used for hot water. Boilers use either pre-mix burners in condensing boilers, or package burners in both condensing and non-condensing boilers. It was considered that it will not be economical to convert non-hydrogen-ready boilers to hydrogen and they will need to be replaced (Ryan & Iliffe, 2020). However, it was considered that all other appliances are likely to be able to be converted to 100% hydrogen appliances cost-effectively. This is a conclusion that is significant for the current FFCRC project with respect to investigation of retrofitting appliances. It is also worth noting that boilers are likely to account for a larger fraction of the commercial appliance landscape in the UK than in Australia, due to the greater need for space heating in the UK. The numbers of commercial appliances in use in Australia has been difficult to quantify.

Hy4Heat WP6 deals with industrial applications and includes many types of dryers, ovens, kilns. A report from Element Energy, Advisian (Worley) and Cardiff University outlined estimated costs of conversion to 100% hydrogen (Durusut, 2019). They estimated that there are approximately 4300 pieces of industrial heating equipment in the UK rated at more than 1 MW and supplied from the < 7 bar network. Again, the segment above 1MW rating has a large percentage of boilers. There are approximately 1400 steam boilers and 600 hot water boilers rated above 1 MW in the UK. For a range of industries, the estimated cost of conversion averaged approximately £150,000 for 1MW or £600,000 for 10 MW. However, since Hy4Heat is only concerned with 100% hydrogen, it did not consider potentially lower costs for retrofitting for blends of hydrogen and natural gas. The types of industrial natural gas users in order of most frequent to least in the UK were identified:

- Boiler (steam)
- Oven
- Boiler (hot water – they call these “boilers” even though they are in-fact water heaters)
- Direct dryer
- Kiln ceramics
- CHP

- Furnace - metal melting
- Furnace - glass
- Kiln - lime
- Indirect dryer
- Kiln other

Potential issues for 100% hydrogen were identified:

- Low radiant heat transfer
- Low convective heat transfer due to lower air requirement. The use of flue gas recirculation or higher excess air can be considered, but will also lower temperatures
- Water in flue my damage some products
- NOx emissions may be higher
- Some users require onsite demonstration trials (particularly if direct fired), but others are happy with guarantees from OEM testing (particularly indirect fired)

1.4 Research gaps and future plan

Typically, 20 mol% hydrogen is targeted for injection trials in Europe and the UK. The THyGA test program in Europe plans to test some appliances with blends up to 60 mol% hydrogen. In Australia, the new HILT CRC will investigate industrial high temperature users with large % hydrogen. However, in all these cases, results will not be produced for some time. As such, it is also prudent to test some appliances or burners to determine a workable maximum % hydrogen in Australia, while focussing mainly on lower % hydrogen blends. Another step is 100% hydrogen appliances, some of which are being developed already overseas.

The current work surveyed the types of industrial and commercial end-users in Australia and categorized appliances and burners so that future evaluation can be targeted at representatives of larger groups. It then presents a costed proposal for assessment, testing, modelling of Type B appliances, burners and ancillary equipment with blends of 10 mol% hydrogen and above. The methods to be used in the proposed project will include modelling, experimental testing and development, whilst also keeping abreast of developments elsewhere.

The motivations for these tests, assessments and models are to:

- Ensure planned 10 mol% hydrogen injection pilot trials can proceed.
- Determine the upper limit in %hydrogen content for current certifications to still be applicable and for process performance and emissions to be acceptable.
- Determine if there are relatively simple modifications that can extend the blending range.
- Investigate economic retrofit options for some appliances for 100% hydrogen duty.
- Provide feasibility studies for large scale end-user trials.

2 TECHNOLOGY ASSESSMENT

2.1 Type B appliances – variety of burner sub-types

The focus of this project is non-pressurised combustion (since University of Melbourne projects are focussed on pressurised combustion in engines and turbines). In a previous report for project RP1.4-02 (Panek et al. 2020), non-premixed, premixed and partially pre-mixed (atmospheric naturally aspirated, induced draft and forced draft) and nozzle mix burners were presented. Details were also given on designs and expected effects of hydrogen addition, such as increased flame speed and reduced stoichiometric air requirement, for some examples. For practical reasons, in many cases it will be necessary to test burners rather than whole appliances or kilns or furnaces.

There are many types of burners used in Type B appliances with a range of different descriptions. AS 3814:2014 has the following examples:

- Atmospheric burner – all air is provided by the inspirating effect of the gas and/or natural draft (i.e. there is no fan anywhere, nor compressed air).
- Induced draft burner – use a suction fan to provide some air
- Forced draft burner – use a mechanical means to supply all of the air under pressure

Typical burner technology definitions and categories (Hazlehurst, 2009) are:

a) Diffusion – have separate air and fuel streams through the burner. Only a small amount of primary air is introduced through the burner, and is not mixed with the fuel. The rest of the air is supplied through a larger inlet which delays mixing and produces large and radiant flame in kilns and furnaces.
    - Used in cement, glass, alumina calcining, smelting, rotary kilns
    - Most of the air is entrained into the flame in the combustion chamber and is not introduced through the burner, e.g. – rotary kilns, glass tanks – gas at up to 10 kPa (Hazlehurst, 2009) into high T air, neat gas burners (probably fairly rare).

b) Atmospheric natural draft partial premix – gas at relatively low pressure, e.g. 1 - 2 kPa entrains 50 -55% of stoichiometric air, with additional air entrained after leaving the burner, examples – the majority of industrial burners – drilled bar, single port (Bunsen), ribbon ported, ring, assembles of drilled.
    - Burner port loading is about 10 MW/m^2, but increase if use less entrained air.
    - Very high port loadings – retention burners using some form of stabilisation through bluff body etc, often with a small fraction of the gas to provide a stable attached flame, Ribbon burners do this too – small auxiliary flames and large ones from diff size openings.

c) Pilot burners – can be natural draft atmospheric or forced draft.

d) High gas pressure, natural draft. A gas pressure of about 2 bar entrains enough air to be fully premixed.

e) Partial premix with ratio control of fuel air mixing to provide a non-flammable fuel-rich mixture – have been used in past after converting from manufactured gas to a gas with higher WI (i.e. natural gas), so that the new gas can be diluted down to the same WI as the original – but not relevant for the current work

f) Air blast burners (fully premixed)– air at about 7 kPa is supplied from a fan and entrains the gas producing intense small flames (i.e. full stoichiometric mixing) – used on heat treating and annealing and re-heating furnaces to produce high temperatures with compact flames.

g) Typically used with quarls or refractory tunnels. Radiation from the hot refractory stabilises the flame. If used without quarls, normally a Retention or non-blow-off tip is used. These have a small axillary flow which acts to stabilise. They are metal – so used without being fully enclosed to avoid high temperatures. Assuming furnace is atmospheric, control is simple, gas entrainment rate is linear with air, and can be adjusted manually, but is then linear. Need non-return valve on both supplies.

h) Nozzle mix (including package burners) – all air and gas supplied at pressure separately to the burner exit which is normally with swirl into a quarl to create rapid mixing between fuel and air. The quarl aid stability by providing recirculation and radiation to incoming fuel. This can result in a small blue flame, but only if there is rapid mixing. Different registers may have different air velocities and varying the air ratio between registers can alter flame length and intensity. Often flue gas recirculation or mixing related NOx control measures are also used. They are highly adjustable and have high intensity. Specific types include:

i) High velocity burner – Tolley Fig 4.25 – full combustion in a metal can and quarl, then high velocity gases out to cause turbulence in the furnace. Can operate on high excess air.
j) Flat flame burners to avoid impingement
k) Radiant burners – used for space heating, grills, high temperature drying - supplied by either an atmospheric injector or and air-blast burner. Types are: porous refractory, perforated refractory tiles, wire gauzes (lower temperature grills and space heaters), catalytic combustion (for LPG, whereas Natural gas has methane slippage), high temperature porous medium burners
l) Radiant tube burners for indirect heating – many types use nozzle mix or air-blast burners (or FlOx).
m) Self-recuperative
n) Regenerative
o) Package burners – have own fan, control system and valves

The wide variety of burner types are used in furnaces and ovens as illustrated by the list above. Many different types of furnaces and ovens are used, with a small selection listed in Table 1 (Green).

Table 1 Some types of furnace uses and their characteristics

Glass	Many variations on regenerative and recuperative
Batch	Heat treatment, drying, calcining ceramics
Direct fired	Side-fired, over-fire, underfired, limited to about 1000ºC
Indirect fired	Radiant tube or muffle
Protective Atmosphere	Heat treatment of metals in indirect furnaces. Gases used are hydrogen, dissociated ammonia, reducing gases - combinations of H_2, N_2, CO_2, CO, CH_4

2.2 Influence of hydrogen on burner performance

Hydrogen has wide flammability limits, low stoichiometric air requirement, and high flame speed. These properties have been well documented, including in the final report of RP 1.4-02 (Panek et al. 2020), so do not need to be elaborated on further. However, for addition of up to 20 mol% hydrogen to natural gas, the effects are not large and it is hoped that burner operation will not be affected. However, performance in terms of emissions and heat transfer is likely to be affected to some degree. In contrast for 100% hydrogen the effects of burner operation are very significant, and it renders the design of partially premixed burners a very difficult undertaking, which may not be practical in some cases and more likely to be replaced by another type of burner design, for example non-premixed flames hydrogen flames, which are very stable. The next section involves a detailed review of one type of another burner category – fully premixed burners.

2.3 Detailed review of premixed radiant burners

Premixed radiant burners were reviewed in some detail in FFCRC RP1.4-02 (Panek et al. 2020), but a further detailed review was undertaken in this project, since they are potentially more susceptible to a change in fuel characteristics than other types because they are fully premixed. Tests with measurement of temperature and emissions may be necessary to quantify effects if hydrogen addition at the 10 mol% and 21.7 mol% levels, and to determine the maximum hydrogen blend ratio that can be used with no changes.

Gas-fired radiant burners (RB) are widely used in industry for thermal processing of materials such as rolled steel, textiles, paper and food as well as for paint drying, power coating, plastic forming and industrial space heating. RBs are typically designed for operating temperature below 1100 °C where uniform heat flux profiles are needed and/or where direct contact between the object to be treated and the flame must be avoided. RBs are based on the concept of internal heat recirculation and are typically configured in a premixed mode. A fresh mixture of gas and air is forced through a gas-permeable material (emitter) and burns within the outflow surface. The emitter, heated by high temperature combustion products, becomes highly incandescent and emits infrared heat into the surroundings (according to Stefan-Boltzmann law). A portion of the heat from the combustion zone, through conduction within the solid and solid-to-solid radiation, flows upstream preheating the fresh mixture through convective heat transfer between solid and gas phase. The thermal conduction within the emitter provides homogenous conditions for combustion and uniform surface temperature. Depending on the emitter design, mainly regarding the structure of gas-passage or a pore network, gas-fired RBs can operate with lean mixtures with equivalence ratios in the range 0.6 – 0.99, heat flux in the order of 100 – 500 kW/m^2 (although specific designs can achieve up to 1 MW/m^2) firing rate in the range 3-70 kW and superficial speeds of fresh mixture of 0.03-0.5 m/s. The nature of the emitter (either a metallic fibre or a porous ceramic material), dictates the surface combustion temperature and start-up time (short-wave RBs feature a surface temperature in the range 800-1100°C and start-up time less than 1 min).

A key performance parameter is the radiant efficiency, i.e., the ratio of the power emitted in the form of radiation to the total power of combustion. When RBs operate in the radiant mode, i.e., when the flame speed is equal to the velocity of the combustible mixture within the porous layer and the process is *surface stabilised*, the radiant efficiency can achieve values of 70-80%. A detailed review of RBs performance is provided by Maznoy et al. (2020). On the other hand, an increase in the firing rate above a certain level, leads to a decrease in the radiant efficiency because the flame stabilises above the emitter with only a small amount of radiant heat emitted (*blue flame regime*). In this regime, the heat is mainly transferred through convection leading to higher flame temperatures, responsible for higher thermal NO_x emissions. Stable operations for RBs are limited by flashback (at high firing rate and/or low air to fuel ratio) and by lean blow-out (at high air to fuel ratio). Under stable operations, RBs typically provide ultra-low NO_x (10-100 ppmv @ 3% O_2) and fuel flexibility. In specific commercial design, the emitter can be coated with catalysts to enhance the combustion performance, allowing leaner mixtures to be burnt, hence producing lower NO_x emissions (because of lower oxidation temperatures).

Typical industrial scale usage of RB technology is in the range of 0.3-1 MW, depending on applications. *Australian Paper* is the largest paper company in Australia and Victoria's largest industrial user of natural gas with up to 20% of the total gas consumption is typically used for thermal processing and/or drying[3]. Other examples of gas users employing this technology are plastic producers (e.g., *George Fischer Pty Ltd* and *Vinidex Pty Ltd)*, which are also preferred suppliers of nylon and polyethylene/polyamides for *Jemena[4], and* bakeries (typically using ribbon burners which are a specific design of RB).

Limited data on the impact of hydrogen blending on risk/safety and performance of RBs are available to date. Some of the key studies are reported below (noting that some data were already summarised in the final report of the FF-CRC RP 1.4-02 (Panek et al. 2020):

- The latest *THyGA EU 2020* report suggests that the performance of premixed RBs can be significantly influenced by hydrogen admixture, particularly for designs featuring pores/holes in the burner body. This is because the flame speed varies, depending on the amount of hydrogen, and the safe operating condition being Peclet < 65 may be challenging to achieve. For significant levels of hydrogen addition, the size of the holes might be adjustable for a certain range, but it could be very limited. However, no data on minimum and/or maximum level of hydrogen tolerated by existing burners was reported.
- For catalytic RBs, Saint-Just and Etemad (2016) reported that, if hydrogen is to be used instead of natural gas, only counter-current convective diffusive-type heaters, i.e., non-premixed burners where fuel and air streams are supplied from opposing sides of the catalytic layer, would be suitable for safe operation. They also reported that there is no incentive to use pure hydrogen for RBs, as the relatively low-temperature operation with natural gas does not entail the creation of pollutants nor large CO_2 emissions. However, no experimental data were reported.
- Brockeroff and Emonts (1994) developed and tested a 10 kW-scale RB using a porous material. Tests were performed with natural gas/hydrogen mixtures with an H_2 content in the range 0-80% by volume. For an air ratio of 1.1, the maximum firing rate achievable without flashback was 60 and 160 kW/m^2, respectively for an H_2 % of 80 and 30. The NO_x emissions were found to decrease with an increase in H_2% while CO was found to slightly increase. This because of the reaction zone being moved upstream with an increase in hydrogen, resulting in a relatively lower temperature. They also suggested that

[3] https://esdnews.com.au/looks-good-on-paper-creating-energy-from-waste

[4] https://www.aer.gov.au/system/files/JGN%20attachment%202%20%2028%20April%202010.pdf

operations with 100% H_2 could be achieved by using a sufficiently active catalyst and by limiting the burner operation to low power density (e.g., 60 kW/m^2) together with other measures such as putting thin walls with holes in the inner part of the porous structure.

- Arrieta et al. (2017) studied the performance of an RB with a catalytic porous inert media operating with blends of NG in equimolar proportions with three high hydrogen content syngas (H_2/CO = 1-3). They found that the addition of syngas did not significantly affect the flame stability and temperature profile within the RB. However, significant differences were observed in terms of radiant efficiency and pollutant emissions, with higher efficiencies and reduced CO emissions found for hydrogen blend mixtures. Gauthier et al. (2007) studied a similar system up to 500 kW/m^2. Despite the lean blow-out limit being extended, the radiant efficiency dropped when NG/H_2 blends were used because the majority of the operations took place in the *blue* mode rather than the radiant mode (for H_2 > 20% by vol.). The latter could not be achieved for H_2% above 80% by vol. Also, the flashback limit was shifted towards lower equivalence ratios with H_2, particularly at high firing rates. Similar to other works, the NO_x emissions were not significantly altered by the use of blends while CO emissions were reduced in the presence of H_2.
- Keramiotis et al. (2015) studied a two-stage porous RB with a 10ppi foam employing both CH_4 and a mixture of CH_4/CO/H_2 with up to 20% by vol of H_2 content as fuels. They varied the thermal load and the and excess air ratio in the range 200-800 kW/m^2 and 1.1-1.8, respectively. They found that the fuel composition greatly influenced the radiative burner performance because of the different burning velocities and hence the location of the stabilisation point inside the porous media.
- Francisco et al. (2010) studied the performance of a non-catalytic porous RB fed with NG and NG plus low calorific syngas (H_2 value up to 10% by volume of the total). They found that, for the specific burner design investigated, the macroscopic flame shape was approximately the same with and without hydrogen addition although the flame moved further upstream from the burner exit when H_2 was present. This is caused by the increase in the laminar flame speed as the H_2 content in the mixture increases. For a Wobbe Index varying from 5 to 44 MJ/Nm^3, it was found that stable operations are possible up to 260 kW/m^2, revealing fuel interchangeability, although the radiation efficiency reduced with H_2 enrichment. In addition, the pollutant emission indexes decreased with the use of H_2-enriched mixtures. Similar results were found in a subsequent study (2013) in which the performance of the same porous RB was investigated under confined hot conditions.
- Echigo et al. (1983) developed a porous RB whose combustion chamber contained a ceramic plate burner followed by a layer of stainless-steel mesh to facilitate heat recirculation. The steel mesh was surrounded by an arrangement of heat exchanger tubes for preheating the incoming combustion air. They found that the addition of hydrogen to NG increased the lean limit of the burner (from 0.284 to 0.1).
- Three different RBs were tested by Rørtveit et al. (2002), namely a low-NOx fibre burner (12 kW), a non-catalytic porous inert media (PIM) burner (12 kW) and a catalytic one (4 kW) to assess the impact of hydrogen admixture on NO_x emissions. NG/H_2 blends of up to 20-30% of H_2 by vol. were tested. No significant effects on NO_x emissions were found in the non-catalytic PIM and fibre burners while the emissions were reduced in the catalytic PIM burner when hydrogen was used.

The available data to date at laboratory-scale would suggest that operations with up to 10 mol% of H_2 are potentially feasible without a significant impact on performance, emissions and stable operations (including blow-off or flashback). On the other hand, ≥20 mol% of H_2 will potentially lead to a reduction in performance (lower radiant efficiency), and a shift of the flashback limit towards lower equivalence ratios. No data are available for 100% H_2

Despite the relatively large amount of data available in the literature, a complete assessment of (i) the compatibility of existing RBs with 10mol% hydrogen/NG blend, (ii) the maximum vol% hydrogen in the NG/H_2 blend possible without making any changes to equipment, and (iii) the maximum mol% hydrogen in the NG/H_2 blend with minor changes to the equipment is not presently available. Also, the data available suggest that these limits will be specific to the RB technology, shape and firing rate investigated. An experimental program employing different designs of commercially available premixed RBs would be ideal to map their performance in terms of radiant efficiency, pollutant emissions and fluxes as well as flashback, blow-off, radiant and blue regions as a function of firing rate, equivalence ratio and % of hydrogen added to NG. The proposed project will inform on the compatibility of these existing RBs with 10mol% hydrogen/NG blend and the maximum mol% hydrogen in the NG/H_2 blend possible without making any changes to equipment. It will also inform at which fuel composition would be best to switch from a premixed conventional design to either designs, such as non-premixed design or new premixed design specifically design for large amount of hydrogen (up to 100% H_2).

2.4 Technology – large Industrial users

FFCRC project RP1.4-03 is addressing the suitability of hydrogen blends for calciners in alumina and cement industries as an example of high temperature processes using pre-heated air and diffusion flames. Other industrial applications using other types of burners will be investigated in the current project. These include many applications where burners are used in different types of furnaces, kilns, heaters or boilers.

2.5 Hydrogen technology options for commercial applications

100% hydrogen boilers have already been developed by Bosch and Baxi amongst others. Consequently 100% hydrogen boilers do not need further development work in Australia, but could be imported for demonstration and testing.

Many burner manufacturers have burners suitable for up to 30% hydrogen in natural gas, and other burners under development for higher concentrations of hydrogen. Some burner manufacturers are developing products for 100% hydrogen. Examples include Honeywell (having purchased Maxon and and Kromschröder), who claim to have a range of hydrogen-ready and hydrogen-capable (i.e., small changes required) burners and control systems covering industries as diverse as incineration, paint bake ovens, process heaters, dryers, bakery ovens, coffee roasters, glass melting, metal melting and treatment, dryers in the pulp and paper, construction, and textile industries[5]. The burners types that are more readily adaptable to 100% hydrogen duty are diffusion, duct, and nozzle mix burners. This includes oxy-fuel burners for glass kilns and melting application, radiant tube space heaters, but not premixed burners.

Another example, Fives Combustion, have used "Pillard LONOxFLAM® G2" burners for 100% hydrogen duty in a chemical plant[6]. This is an example of being able to adapt a nozzle mix burner to hydrogen. In general, this should be possible for all nozzle mix burners, but in many cases may also require changes in nozzle geometry. Performance and emissions then have to be optimised for each process, and may not be suitable for all processes.

Obtaining 100% hydrogen burners for university testing many not be feasible because the burner companies prefer to do their own development and manage the "story" associated with it. However, it will be possible to test the principles experimentally and thereby provide insight for FFCRC partners into potential costs of retrofitting or designing new burners for 100% hydrogen.

2.6 Commercial catering equipment

AS4563:2004 lists many types of commercial catering appliances. For example, boiling tables and cooking tables, salamanders, grillers and toasters, solid grill plates and griddles, ovens, boiling water units, stockpots and brat pans, atmospheric steamers, fryers, food warmers and pasta cookers.

Many of these are Type A appliances, i.e. they have an acceptance (i.e. mass certification) scheme, so will be covered in the FFCRC Type A testing project (RP1.4-05). The examples of commercial catering equipment that are in the Type A testing program, supplied by GAMMA members, are a cooker, fryer and pasta cooker.

If there are found to be representative Type B commercial catering appliances that are significantly different in burner design or operation to those tested in the Type A project they will be included in the test program proposed by the current work.

2.7 Carbon emission reduction: electrification vs 100% hydrogen

Many large-scale industrial processes using air pre-heat operate at very high temperatures and this is generally easier to provide via combustion than electric heating. However, in some cases, electrical heating can be used.

---

[5] https://thermalsolutions.honeywell.com/content/dam/hpsbt/en/documents/downloads/HONEYWELL-THERMAL-SOLUTIONS-Harnessing-the-promise-of-hydrogen-to-reduce-global-emissions.pdf

[6] https://combustion.fivesgroup.com/ko/news/combustion-news/expertise-in-hydrogen-combustion.html

For example, resistive heating can achieve temperatures of 1400ºC, but is only applicable for clean air and non-dusty processes, because particles will destroy the resistive elements. Electrical heaters generally have high capital costs, especially as more exotic materials are required for higher temperatures. (Electrical plasma heaters can provide high temperatures, but are still in the R&D phase.)

Commercial sector indirect fired appliances generally operate at low enough temperatures to have electrical equivalents. It is likely that both hydrogen and electrical appliances will be used in large numbers in the commercial sector, and in some cases hybrid units employing both hydrogen and electricity may be used.

Hydrogen retrofits of gas appliances or new hydrogen appliances may be preferable where:

- Electrical upgrades are expensive – e.g. upgrading electrical transmission and distribution networks and electrical supply to site or on-site
- Electrical heating elements are expensive,
- Heat transfer limitations (e.g. from reverse cycle heat engines or from electrical heating elements) may render electrical units unsuitable.

Electrical options may be more suitable if:

- Electrical upgrades are not required or are less expensive than new hydrogen infrastructure
- A gas-fired unit is near end of life and has a ready electrical replacement
- There is access to cheap electricity or on-site solar PV to supply some of their electrical demand.
- Tenewable hydrogen price is high
- There is no existing gas distribution network to re-purpose.

Hybrid hydrogen/electric appliances may have the capability to switch between or change the proportion of either electricity or hydrogen depending on fluctuating electricity prices, and onsite generation of both electricity and hydrogen. Hydrogen may be stored on-site to buffer electricity price fluctuations. This is likely to be a niche that can be investigated in a separate project.

3. TYPE B APPLIANCES IN AUSTRALIA

3.1 Appliances in hydrogen injection pilot trial areas in Australia

There are several pilot projects in Australia aiming to blend up to 10 mol% hydrogen into natural gas, which include commercial and industrial equipment:

- AGIG is developing a hydrogen injection plant at Gladstone, Queensland that will provide up to 10 mol% hydrogen to entire the network, including Type B appliances.
- The Australia Hydrogen Centre has received $1.28m funding from ARENA[7] to perform feasibility studies on blending 10 mol% hydrogen into regional towns and gas networks in Vic and SA and on providing 100% hydrogen to networks in Vic and SA.
- Jemena plan to inject hydrogen into the JGN network from mid-2021, including 7 industrial users (brick kilns), 39 commercial users (Bakeries, Distilleries, Kitchens etc) and residential users. Larger customers have already shown support for further research (Panek et al. 2020)
- AusNet has a blending project underway in Ballarat.
- ATCO's Clean Energy Innovation Hub and Park in WA includes some engines, but future projects are likely to also include other commercial appliances.

Discussions with network operators and local Regulators and assessors identified many appliance types in pilot trial areas in Australia. Detailed information regarding make and model numbers is not readily available, but a consolidated summary of the types of appliances present is given in Table 2.

Table 2 Type B appliances in hydrogen injection pilot trial regions in Australia

High efficiency Boiler	Paint spray booths	Arc furnace
Condensing hot water heater	Powder coat drying oven	Burn-off furnace
condensing boiler	Paint drying oven	Laminator for plastics
Hot water heater	Indirect air heater for metal drying	Annealing furnace
Pizza ovens	Scrap metal heater	Exothermic atmosphere generator
Coffee Roaster	Brick Dryer	Endothermic gas generator
Rotary rack baking oven	Grain Dryer	Cremator
Continuous conveyor baking, drying, grilling	Clothes dryer	Incinerator
Various commercial catering	Process Ovens	
Tank heater	Curing oven	Air conditioning - engine driven
Immersion tube heater	Powder cure oven	Generator
Hot oil heater	Drying oven	Turbines
Oil heater with package burner	Concrete curing system	
Direct fired space heaters		
Indirect fired space heater		

3.2 Appliances in Australia

The list of appliances in pilot trial areas was expanded through prior knowledge and discussions with industry advisers, certifiers, regulators and suppliers, and referencing those listed in the relevant Australian Standards.

Table ***3*** shows this expanded list with appliances categorised by broad combustion type (premixed, partially pre-mixed etc), and with more details about burner types and with some suppliers listed. The expanded list illustrates

[7] https://arena.gov.au/projects/australian-hydrogen-centre/

that the appliances in pilot trial areas are fairly representative of those throughout the broader economy. The types of burners used in most of these appliances are represented in the list to be tested in the screening tests (see Section 2.2 -1b on page 6 of the Proposal for future work).

The aim of categorising appliances and burners is to find common or representative types, so that the testing and assessment program can be constrained within practical limits, whilst still being as representative as possible.

Then the first task in the proposed future work is to perform an expert assessment of potential issues, followed by screening tests. A key point is that all combustion systems are some variant of the key types listed, which has the potential to reduce the required testing program to a manageable level. It will also be important to assess common burner control systems and flame detection systems.

Table 3 Appliances in Australia, categorised

Appliance /application	**Combustion type**	**Example suppliers**
Pressurised combustion		
Co-gen, tri-gen	Engine	
Co-gen, tri-gen	Turbine	
Co-gen, tri-gen	Microturbine	Capstone
Air-conditioner	Engine	Yanmar
Generator	Engine	Kohler at Gas Train (from Clark Energy), CD Power Generac in WA
LNG production (huge user of NG)	Compressors, refrigeration	
Diffusion / non-premixed		
traditional regenerative glass furnaces, alumina calcining, smelting, rotary kilns (cement, lime, mineral processing, plasterboard)	Diffusion • some have primary air as nozzle mix – e.g. rotary kilns • Glass often just 2 co-annular gas streams	
Heat recovery Steam Generators (e.g. in Co-gen plants), driers	Duct burners (non-premixed) – linear and grids - fuel exits on lee side with flame holder	
Direct Driers	Duct burners	
Partial premixed		
Pilot burner for large ovens and kilns	Atmospheric partial premix with ID fan and pressure switch	
Tumble dryer etc	Normal package burner. Some are partial premix with ID fan	
Coffee roaster	Some older smaller ones partial pre-mixed – latest are package burners	
Porous radiant burners – stadium space heaters and low temperature drying of paints, textiles, paper, heat treatment of steels, plastic forming, conveyors	Atmospheric partial premix – work like a grill in a Type A oven (or some BBQs have one under a hood)	
ribbon burners –wire, glass blowing (Ribbon burners are high energy and don't flashback and don't lift)	Some are atmospheric partial pre-mix venturi into a mixing chamber and then multiple exits (others are forced draft)	
water bath heaters in the gas distribution system, range from 3-10 GJ/h (Potential for full-scale test)	inspirated premixed burners with tall stacks to provide natural draft (others are forced draft nozzle mix)	
metal treating – galvanising lines (e.g. burners used for indirect heating of galvanising bath)	some atmospheric partial premixed burners with a flame retention nozzle on the end - and some forced draft nozzle-mix	
Pizza ovens (Flame luminosity may be important – so this may change. Quick response of gas compared to electricity, with automatic control is a plus. Gas fired units may be cheaper to buy and connect.)	A variety of curved line burners or multiple simple partially premixed burners firing upwards.	Euroquip
Direct fired gas heaters	Multiple partial Premix venturi tubes	AIRA Dravo by Seeley
Process Ovens	Some are partial premixed	
Plasterboard manufacture	Some are FD partial premix?	

Paint spray booths	Most commonly use Riello package burner (FD) firing into a heat exchanger which heats air than circulates over the parts to be baked Or IR gas burner – forced air partial premix burner heating steel that radiates. Some use atmospheric direct air burners – i.e. inspirating type with no fan. Some use catalytic IR burners mostly firing LPG	Aussie Spray booths, Lowbake, Seetal, Complete booth services, Truflow
Hot oil heater	Atmospheric partial premix	Thermal and Pressure Engineering, Consolidated Fire and Steam
Brick kiln burners		
Continuous conveyor baking, drying, grilling	Pre-mixed Gas mesh - like a domestic griller?	(Wesmartin) Furnace Engineering
Fully Premixed		
Strip line burners for metal heat treating, laminating plastics, plastics forming, low temperature drying of paints, textiles, paper	Fully premixed ribbon burners and other porous burners, Possibly some air-blast	
Burners for singeing textiles	Fully or partial premixed	Furnace Engineering
Strip line burners for metal treating	Radiant tube burner – some use "MILD" or "Flox"	
Furnaces	Premixed Radiant wall burners tolerant to H2 up to 70% (RP1.4-02).	
Process heaters	Radiant wall burners, custom made, fired heaters such as SMR, ethylene crackers, process heaters in refineries, e.g. in Kwinana	
Endothermic gas generator (used for metals treatment – e.g. carburizing or to prevent oxidation, carburizing (case hardening).	Uses a retort with catalyst and requires a carbon-based gas.	
Forced Draft Nozzle Mix (including package burners) – some also ID fan		
Utility scale boilers – only 2 left in Australia	Nozzle mix or tangential	
Industrial steam raising boilers (some industrial ones also used to generate electricity) + Commercial sector boilers used for steam – circular burners with range of swirl air, FGR or internal FGR for NOx control	Older are Nozzle mix Newer are package burners Small versions are FD only, larger may be both FD and ID	Trevor, Maxitherm, Enertech, Tomlinson, Cleaver Brooks
Water bath heaters in the gas distribution system - nozzle mix forced draft burners are used in some water bath heaters	Nozzle mix	
Fired heaters – have a radiant and convective section. NOx control techniques similar to boiler burners	Nozzle mix	
Metal treating – galvanising lines have some premixed burners and some nozzle-mix	F.D. Nozzle mix	
Strip line burners for metal treating	Nozzle mix	Major Engineering
Controlled atmosphere furnaces	Nozzle mix	Major Engineering
Self-regenerative burners, which have a large mass of refractory material - used in pairs in a cycle (flue gas heats out of service burner refractory). Applications include continuous and batch metals heating and forging operations and ceramics and pottery kilns	Nozzle mix	Orora (Gawler)
Self-recuperative burners (flue gas heats incoming air)	Nozzle mix	Maybe not in Aus?
Side-fired glass kilns with recuperators, brick tunnel kilns, ceramics kilns and multiple hearth magnesia calciners	Nozzle mix	Traditional glass kilns
High efficiency Boiler	Package burner	

Condensing boiler - can put modular multiple units to partially replace old boilers. (Condensing boilers will be even more efficient than non-condensing boilers with blends of hydrogen since more of the flue condenses. Flue design will need to be assessed for 10% and 21.7% hydrogen	Multiple premix burners controlled by air gas ratio valves. Much more efficient than non-condensing.	Baxi, Applied Heating, Moorea
Hot water heater & condensing hot water heater	Package burner	Chappee, Raypak, William Boby, Hunt, Hoval, Rheem, Aira
Cremator	In a small furnace (incinerator) + package afterburner for stack	
Incinerator		Megtec
Immersion tube burner	High velocity burner (Tolley Ch 4, Fig 4-25) – exhaust gas at high vel. for convective heating	Garnic
Indirect fired drier – i.e. combustion products heat coils containing fluid to be heated	Package burner (can also be atmospheric or nozzle mix)	
Coffee Roasters	2 package burners, one for roasting, then an afterburner in flue for odour and burn light husks	Probat
Radiant space heaters linear or U-tube	small package burners – flue gas down tube which acts as radiant heater	
Tumble dryer	Package burner (or atmospheric with ID fan)	Jensen, Passat, Lavatech
Ironing machines	package burner with Thermal oil heater	
Furnaces – reheating, annealing, melting, forging, reverberatory, arc, burn-off	Package burners	Furnace Engineering
Furnaces – reheating, annealing, melting, forging, reverberatory, arc, burn-off	Nozzle mix	
Ovens and furnaces, e.g. curing ovens, paint drying, powder coat drying	package burners	Riello, Furnace Engineering, Garnic
Timber drying kiln – may be more likely to use waste wood	?	
Plasterboard manufacture	Package burner	
HVAC indirect air heater	Some are package burners, others are atmospheric	
Process ovens	Some use package burners	Furnace Engineering
Baking ovens, e.g. rotary rack	Package burners, mainly 2 stage package burners – i.e. low fire and high fire option, that don't modulate between Flat bread tunnel ovens -FD package burners	
Grain dryers	Probably package burners	Agridry GrainTech Engineering
Powder cure oven, drying oven	Burner systems not clear	Garnic
Concrete curing system	Probably package burners providing hot combustion gases	Kraft
Methane as a feedstock		
Ammonia production	Steam methane reforming	
Sodium cyanide (3 plants fed via transmission lines)	Reactor (methane+NH_3+ O_2)	
Petroleum refining – hydrogen for hydrocracking	SMR	
Those specifically in AS 3814 or AS 4563		
Process after-burners		
Steam and water boilers		
Duct fired Air heaters and curtain		
Smoke ovens	Atmospheric, some package burners	
Direct fired rotary kilns and ovens		
Special Atmosphere Generators		
Cremators and incinerators		
Steam and Hot water boilers		
Stationary Gas engines and turbines		
Water heaters		
Multi-fuel firing systems		

3.3 Flame detection, burner controllers, valve train components

An assessment of common flame detection and flame safeguard or burner management system (BMS) controllers will also be made in the testing program. AS 4625:2008 (Electronic flame safeguards and flame detectors) describes flame safeguard systems including the provision for flame detection, flame proving and purging. The proposed project will also assess if any changes need to be made to purge times for different fuel blends.

Newer appliances use microprocessors BMS and process controllers (such as LMV Siemens). An assessment of how they deal with, or can be programmed to deal with, variable hydrogen % in the fuel will be undertaken in the future project. Information on gas composition may be required, or potentially a measurement of density could potentially be used to infer it. Some older appliances still use mechanical linkages for air / fuel mixing by controlling air and fuel valves in predetermined ratios. These less accurate than microprocessor controllers, and provide poor control at turndown, resulting in high excess air and hence poor efficiency. They will be phased out. However, there are enough left in operation to warrant assessment and testing with hydrogen / natural gas blends.

The proposed project will assess the performance of ionisation rod, UV and IR flame detectors with the range of hydrogen blends tested. Flame detectors, and their use in Type B equipment can be summarised as:

a. Flame rectification ionisation rod – makes use of a small electrical current which passes through the ionisation rod (positioned in the flame) and in the presence of a flame travels to ground and indicates a flame and can be used to keep the gas valve open. Type A domestic cookers, continuous flow water heaters, and 80% of Type B appliances use ionisation rods. However, it has been shown in UK work that ionisation signal strength reduces with the addition of hydrogen and issues start to emerge for blends with more than 30 mol% hydrogen. This finding needs to be checked for Australian appliances with different blend ratios, and implications need to be identified.
b. Ultraviolet flame (UV) sensors – some package burners, furnaces
c. Infrared flame (IR) sensors – sometimes used in Type B equipment.
d. Photo cell – detects visible light - not used in Type B equipment
e. Thermo-electric - only used in Type A storage water heaters, no longer used in Type B equipment because of the response delay. They work by using the thermocouple millivoltage to operate a solenoid valve.

Valve trains deliver the fuel to appliances, and incorporate instruments for control and measurement. Components include filters, regulators, control valves, block valves, butterfly valves, gate valves, ball valves, check valves, flow meters, flow limiters, pressure transmitters and pressure gauges, various pipe fittings and joining types. Current valve train components include a range of materials, some of which are already hydrogen compatible. Equipment suppliers are developing hydrogen compatible components to replace those that are not suitable and can provide certification where appropriate.

Leakage rates from plastic piping and fittings are being investigated in FFCRC RP3.1. Other parts of RP3 are investigating steel pipelines with respect to corrosion, fatigue, fracture and new instrument development. However, no work is specifically planned in RP3 to test leakage from existing or new valve trains. It is important that leakage rates are low because hydrogen leaks are more likely to ignite than natural gas (unless they disperse rapidly) due to wider flammability limits and a low ignition energy. Part of the proposed test program includes testing of leakage rates of valve trains used in the experiments. The leak test procedure in AS 5601.1:2013 (Appendix E) will be used, which calls for ensuring that a higher pressure than the normal operating pressure can be held for 5 minutes. However, in this case the time will be extended to one hour, and any leakage will be determined by pressure reduction as a function of time. Tests will be done for a natural gas baseline and blends of 10 mol% and 21.7 mol% hydrogen in natural gas. A hydrogen leak detector will be used to find any leaks and remedy them, allowing for a pressure re-test. Tests could also potentially be performed with 100% hydrogen. These leak tests will only provide an early indicative assessment of whether using hydrogen blends in existing valve trains is likely to cause significant leakage problems. It may not be widely applicable because each valve train contains a different range of materials and components, but may assist gauge the likely significance of leakage.

4. CONCLUSIONS

There are a wide variety of Type B appliances in Australia. This project has attempted to identify the major types and to categorise them by burner type so that a representative evaluation program can be conducted.

Typically, 20 mol% hydrogen is targeted for injection trials in Europe and the UK. The THyGA test program in Europe plans to test some appliances with blends up to 60 mol% hydrogen. In Australia, the new HILT CRC will investigate industrial high temperature users with large % hydrogen. However, in all these cases, results will not be produced for some time. As such, it is also prudent to test some appliances or burners to determine a workable maximum % hydrogen in Australia, while focussing mainly on lower % hydrogen blends.

The current work surveyed the types of industrial and commercial end-users in Australia and categorized appliances and burners so that future evaluation can be targeted at representatives of larger groups. It then developed a costed proposal for assessment, testing, modelling of Type B appliances, burners and ancillary equipment with blends of 10 mol% hydrogen and above. The methods to be used in the proposed project will include modelling, experimental testing and development, whilst also keeping abreast of developments elsewhere.

The motivations for these tests, assessments and models are to:

- Ensure planned 10 mol% hydrogen injection pilot trials can proceed.
- Determine the upper limit in %hydrogen content for current certifications to still be applicable and for process performance and emissions to be acceptable.
- Determine if there are relatively simple modifications that can extend the blending range.
- Investigate economic retrofit options for some appliances for 100% hydrogen duty.
- Provide feasibility studies for large scale end-user trials.

The costed proposal for evaluation, testing, and modifications of appliances with 10 mol% hydrogen in natural gas, and with more significant amounts of hydrogen, has been written and approved by the FFCRC Board and given the project number, RP1.4-08. It is described further in Section 6 below (Next Step and Future Work).

5 IMPLICATIONS AND RECOMMENDATIONS FOR INDUSTRY

It is recommended that the costed proposal associated with this work is approved and the work conducted, starting in October 2021.

6 NEXT STEP AND FUTURE WORK

6.1 Proposed Assessment and testing project

A proposal has been developed, based on the types of burners and appliances identified in Australia. It will include testing at up to 21.7 mol% hydrogen as illustrated in Figure 1.

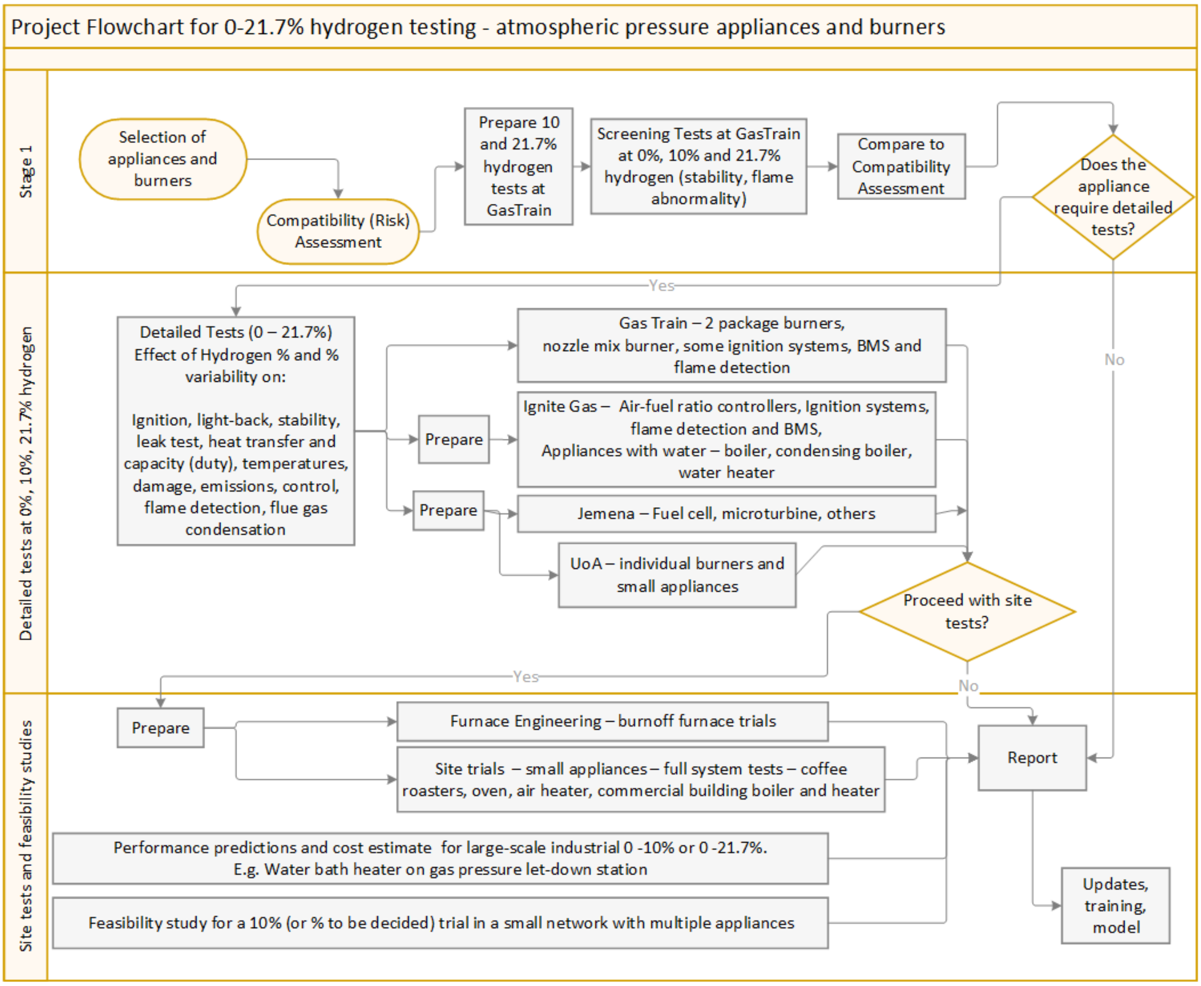


Figure 1. Project plan for testing and modelling with up to 21.7 mol% hydrogen

The aims of that project are:

a) Determine whether current natural gas applications can be used effectively without changes with blends of up to 10 mol% hydrogen in natural gas, including rapid variation in blend concentration between 0-21.7% to account for worst case excursions in blending. The assessments need to consider safety (ignition, pilot, flame detection, shutdown), combustion stability and performance (light-back, control system, air fuel/ratio control, performance, heating performance, efficiency, emissions, flue gas and condensation handling). Tests will mostly use old appliances (but some new burners and modifications and new appliances will be included).
b) Find the maximum % hydrogen in a blend for only a limited number of burner types that may be present in an industrial hub or regional commercial region where local availability of hydrogen may warrant its use before being more generally available.
c) Test effects of hydrogen addition on process performance (temperatures, heat transfer, emissions)
d) Perform feasibility study on larger scale tests

The focus of the first stage of testing is to answer some key questions for compatibility of Type B appliances with 10 mol% hydrogen. The remaining stages extend the research to a wider range of blends and 100% hydrogen.

Prior to screening tests a compatibility (research prioritisation) assessment will be undertaken, assessing potential issues with each type of burner and appliance to help guide the testing program. This assessment will involve Industry Advisers, Type B regulators, collaborators, others in the industry and University staff. Its purpose is to identify appliances or burner or systems that are higher priority for investigation. It will be performed with the separate consideration of Likelihood, Safety-consequences and Reputation loss for each potential issue for each burner type, for 10 mol% hydrogen, 100% hydrogen and for an intermediate blend, as illustrated in Table 4 below, with the panel to discuss and rate each either 0-10 or Z(ero), L(ow), M(edium), H(igh).

Table 4 Compatibility - Research Prioritisation Matrix (consider Likelihood, Safety - consequence and Reputation loss)

Burner or appliance or equipment	Light-back	Control system problem	NOx or CO emissions too high	Flame stability problem	Flame detection problem	Metal temps too high	Process quality or efficiency problem	Flue gas handling or dew point problem	Throughput limitation
Diffusion Non-premixed									
Package									
Nozzle mix (non-package)									
Partial premixed - Natural draft									
Partial Premix – Induced draft									
Partial premix – Forced draft									
Partial premix – surface burner									
Fully premixed - surface burner									
Fully premixed non-radiant (e.g Neon signs, furnaces									
Air blast burner									

Screening tests will be performed on the following types of burners with 10 mol%, 21.7 mol % hydrogen blends and effects of variability in blend ratio, followed by more detailed tests on some of them.

- package burners (these are the most common type of burner used in Type B equipment)
- 1 nozzle mix burner
- Forced draft nozzle mix (e.g., some galvanising line burners)

- Forced draft “high velocity” nozzle mix burner as used in immersion tube burners and some water bath heaters.
- Fully premixed non-radiant burners – these have larger burner port areas than other types
- Air blast burner – uses air at about 7 kPa, compared to most others which are atmospheric.
- Atmospheric partial premixed venturi burner (many uses, e.g., ducted space heaters, pizza ovens, oil heaters, water heaters)
- Atmospheric partial premixed burner with ID fan (e.g., used in tumble dryers and pilot burners)
- Water bath heaters – scaled down version of the inspirated natural draft premixed type with tall stack
- Atmospheric natural draft partial premix porous ceramic radiant burner (e.g., used in space heating, paint drying, metal heat treatment)
- Atmospheric forced draft partial premix porous ceramic radiant
- Ribbon burners (partial premix and forced draft versions)
- Atmospheric partial premix with flame retention nozzle on end (used in galvanising)
- forced air partial premix infra-red burners (catalytic and non-catalytic) used in paint spray booths
- Condensing boiler

Following the tests with up to 21.7 mol% hydrogen, some appliances will also be tested at higher % hydrogen and research on retrofitting some for 100% hydrogen will also be undertaken. The testing will be complimented by production of models of combustion and performance that will be applicable more generally.

For gas blends with higher amounts of hydrogen and 100% hydrogen, the test program can be illustrated in Figure 2. Further details are provided in the full proposal

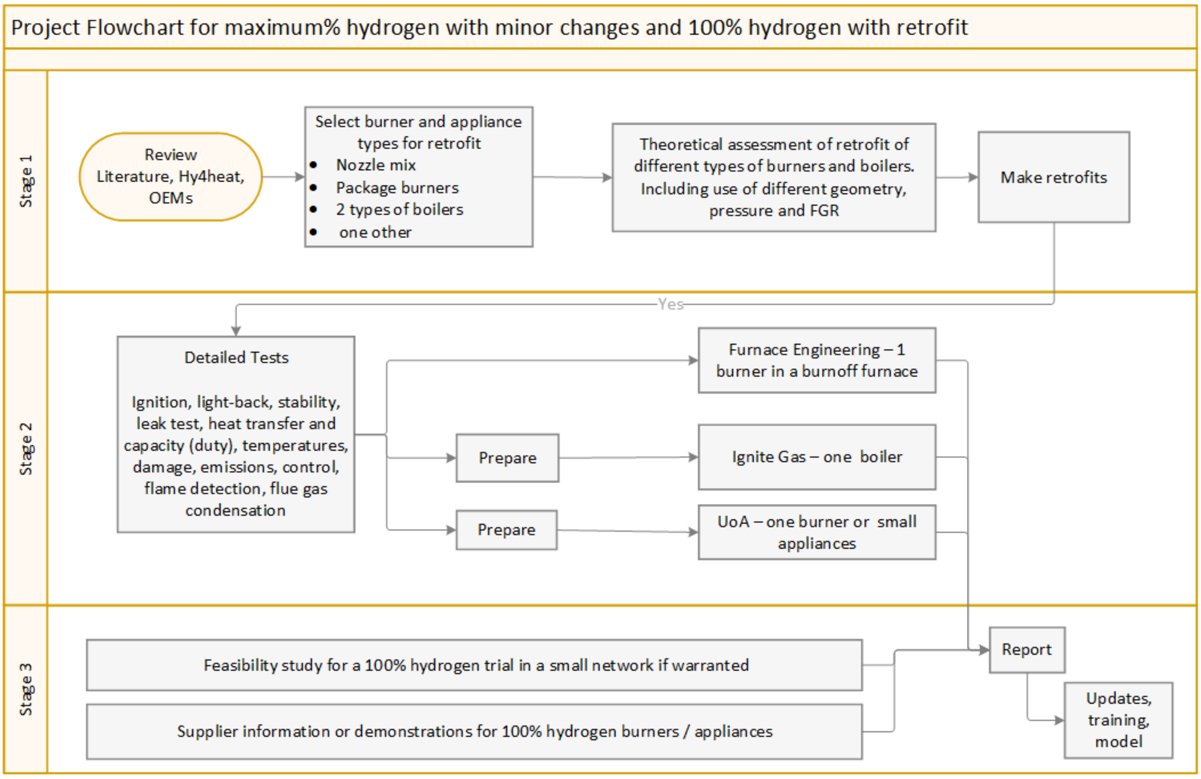


Figure 2. Project plan for testing and modelling with up to 100% hydrogen

7 REFERENCES

Arrieta et al. (2017). Experimental study of the combustion of natural gas and high hydrogen content syngases in a radiant porous media burner. Int. J. Hydrog. Energy, 42, 12669-80

Brockerhoff P, Emonts B. (1994). Test of a premixing radiant burner for the low NO_X combustion of natural gas/hydrogen mixtures. Int J Hydrogen Energy 19:395-8.

Durusut, E. (2019). Conversion of Industrial Heating Equipment to Hydrogen. Hy4Heat.

Echigo R et al. (1983). Combustion augmentation of extremely low calorific gases (application of the effective energy conversion method from gas enthalpy to thermal radiation). Proceedings of the ASME/JSME thermal engineering joint conference, vol. 4. Honolulu; 1983. p. 99-103.

Francisco et al. (2010). On the combustion of hydrogen-rich gaseous fuels with low calorific value in a porous burner. Energy & Fuels, 24 880-887.

Francisco et al. (2013). Combustion of hydrogen rich gaseous fuels with low calorific value in a porous burner placed in a confined environment. ETFS, 45 102-109

Gauthier S, Lebas E, Baillis D. SFGP (2007). Natural gas/hydrogen mixture combustion in a porous radiant burner. Int J Chem React Eng 2007; 5A114.

Green, D.W. (ed) (2008) Perry's Chemical Engineers Handbook, 8 edition, Ch 24

Hazlehurst, J. (2009). Tolley's industrial and commercial gas installation practice. – 5th ed.

Keramiotis et al. (2015). Experimental investigation of a radiant porous burner performance with simulated natural gas, biogas and synthesis gas fuel blends. Fuel, 158, 835-842

Maznoy et al. (2020). Development of a new infrared heater based on an annular cylindrical radiant burner for direct heating applications. Energy 204, 117965.

Panek, P., Smith, N. Ashman, P, Medwell, P, Brear, M., Yang, Y., Talei, M., Gordon, R. (2020). Final Report on FFCRC Project, RP1.4-02, Future Fuel use in Type B and industrial equipment.

Rørtveit et al. (2002). A comparison of low-NOx burners for combustion of methane and hydrogen mixtures. PROCI, 29, 1123-29

Ryan, B., & Iliffe, M. (2020). Understanding Commercial Appliances for UK Hydrogen for Heat Demonstration. Hy4Heat.

Saint-Just & Etemad (2016). Catalytic combustion of hydrogen for heat production. Chapter 10, 263-87, in Compendium of Hydrogen Energy, Woodhead Publishing

Schaffert et al. (2020). Impact of hydrogen admixture on combustion processes. Part II: Practice. THyGA EU Report.

Schaffert, J., Flayyih, M., Burmeister, F., Albus, R., Görner, K., Milin, P., & Schweitzer, J. (2021). Testing programme for hydrogen tolerance tests of domestic and commercial natural gas appliances. THyGA.

Tolley's Industrial and Commercial Gas Installation Practice, Vol 3, Chapter 4, Industrial Gas Burner Systems and their Control.

Future Fuels CRC

Enabling the Decarbonisation of
Australia's Energy Networks

www.futurefuelscrc.com

info@futurefuelscrc.com

Australian Government
Department of Industry, Science, Energy and Resources

Business
Cooperative Research Centres Program