Deep Decarbonisation of Brick Manufacturing Industrial Fuel Switching Feasibility Study

Hydrogen Kiln Test No 1

Public Report prepared by

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Executive Summary

This Feasibility Project trialled the deep decarbonisation of the brick manufacturing process, assessing the feasibility of converting an existing gas kiln to use hydrogen instead of natural gas to fire the bricks.

Michelmersh produces 125 million bricks annually, through gas firing and drying processes, which contributes over 60% of Michelmersh's total carbon footprint. Working with Limpsfield Combustion, and the University of Brighton, the project partners were looking to prove the feasibility that natural gas can be replaced by hydrogen in the manufacturing process.

The Phase 1 (Feasibility) project was broken down into three work packages:

- WP1: Technical evaluation/ pre-feasibility of hydrogen supply to the burner at the site.

- WP2: Investigate the feasibility of retrofitting gas burners used for brick firing to use hydrogen, trialling both a 20% hydrogen blend and 100% hydrogen in a test kiln at Michelmersh's Freshfield Lane site in Sussex. The bricks were compared against control bricks (produced using 100% natural gas) to ensure they met technical and aesthetic requirements and characteristics, with laboratory testing to ascertain their durability and structural performance. Air quality experts from the University of Brighton monitored air quality at Michelmersh's Freshfield Lane site. Emissions were also monitored at Limpsfield Lab.

- WP3: In parallel with the kiln testing at Freshfield Lane during Phase 1, develop and conduct lab testing of hydrogen ready 1050 kW burners, used in the drying chambers at Freshfield Lane.

The Pre-Feasibility report (WP1) identified the hydrogen standards, infrastructure, safety and other requirements / considerations needed to be met for the successful deployment of hydrogen onsite. However, the Pre-Feasibility report found that blending gas onsite at point of use would require a number of demanding engineering considerations. Following an options appraisal, the Project Team agreed that a system of 100% hydrogen with no blending of gases would be a simpler system to design, assemble, test, install, commission and monitor. By de-scoping the blended trials the consortium could focus on the delivery of the highest carbon-reduction process.

A key stage of WP2 was to install the Limpsfield hydrogen-ready burner in the stand-alone kiln and to fire it using natural gas. The natural gas trials showed that firing bricks with natural gas is more complex than originally realised, and that swapping burners is not necessarily a simple like-for-like replacement. Maximum firing temperature, length of time soaking at top temperature, and % air supplied to the kiln are all key parameters, as well as the flame speed and burner output. Repeated natural gas trials were required to vary each parameter to achieve a brick which met the technical requirements of Michelmersh's Freshfield Lane *First Quality Multi* bricks.

Three hydrogen burns then took place, which all resulted in completed burns. Overall, the 3 hydrogen burns showed that it is technically possible to fire bricks using hydrogen – indeed, these bricks were potentially the first ever clay bricks fired with 100% green hydrogen in an operational brick kiln in the world.

Although the three hydrogen trials were successful and produced bricks that met the general technical requirements (dimensions, compressive strength, water absorption) of clay bricks, additional hydrogen trials would be required before a whole-scale fuel switch to hydrogen. This would enable the firing process to be fine-tuned to achieve the specific technical requirements of the bricks being fired, especially with regard to eliminating bloating and producing bricks within the required dimensional tolerances.

Assuming that 100% of the fuel was fired during all burns (and there were therefore no fugitive methane emissions), all three hydrogen burns achieved reductions in carbon emissions of 80 - 84%.

This data was verified by the Air Quality Monitoring results, where CO_2 emissions were directly monitored during all hydrogen trials and during one natural gas burn. The monitoring picked up CO_2 emissions during all firings, including the hydrogen trials. This was due to the carbon fuel within the bricks which was burnt during the firing process.

During the natural gas burn, CO_2 emissions peaked at 13,696 ppm compared to 3,175 ppm during the average hydrogen cycle, suggesting that CO_2 emissions were reduced by up to 75% when hydrogen was used as an alternative to natural gas.

Total NO_x concentrations were notably higher during the hydrogen burns than the equivalent natural gas burn. Total NO_x emissions peaked at ~10,000 ppb during Burn One and at ~12,500 ppb in both Burn Two and Burn Three, compared to a peak of 6,350 ppb during the natural gas cycle.

The final work package (WP3) was to develop and conduct lab testing of the 1050 kW hydrogen ready burners. The initial bench tests firing hydrogen achieved NO_x levels of 125-163ppm at 3% O_2. However, NO_x levels of 39ppm were then achieved by reducing oxygen levels to 2.5% and carrying out flue gas recirculation (FGR). This project helped validate Limpsfield's work developing hydrogen burners, showing that their burners are scalable and can achieve extremely low NO_x levels.

If hydrogen were implemented into the wide variety of different manufacturing sites, equipment and processes across the Michelmersh Group it would reduce gas emissions by 90%, with further replication across the brick and wider ceramic industry leading to significant savings on a national level.

When planning this Feasibility project, the project partners were also considering the next phase if the feasibility were successful. In the Phase 2 (Demonstration) project, the partners would be looking to demonstrate the effectiveness of hydrogen burners at industrial scale. The plan was to trial firing hydrogen using the larger hydrogen burners in the drying process.

However, whilst this Feasibility project was a success, Michelmersh has become increasingly aware of the cost and complexity of working with hydrogen at scale, with still many unknowns regarding its other types of manufacturing methods and facilities. There are increasing zero carbon alternatives to natural gas when heating to the lower temperatures required in the dryers. As a result, Michelmersh are looking to investigate all appropriate decarbonisation options including electric burners and high-temperature heat pumps, before looking to invest significant amount of money in implementing a given method for each of its sites.

Limpsfield Combustion are focusing on continuing to develop their range of hydrogen ready burners, and their expertise in this area. This feasibility project helped validate Limpsfield's work developing hydrogen burners, showing that their burners are both scalable and can achieve extremely low NO_x levels, and has also helped provide them with wider contacts across the burgeoning UK hydrogen industry.

This project was funded by the Department for Business, Energy & Industrial Strategy (BEIS) Industrial Fuel Switching Competition (Phase 1, Feasibility). The programme is part of the £1 billion Net Zero Innovation Portfolio (NZIP) which aims to provide funding for low-carbon technologies to reduce the costs of decarbonisation.

1. Project Overview

In total, the UK brick manufacturing industry produces 1.9 billion bricks a year. Brick manufacturing is an energy intensive process, with high temperature heat (over 1000°C) required at the heart of the process to fire bricks. The fuel required to provide this heat traditionally comes from mains gas, making it also a carbon intensive process.

This Feasibility Project trials the deep decarbonisation of the brick manufacturing process, assessing the feasibility of converting an existing gas kiln to use hydrogen instead of natural gas to fire the bricks. There are no carbon emissions associated with the combustion of hydrogen – resulting instead in heat and water vapour. Hydrogen can also be produced using electrolysis without any carbon emissions.

Michelmersh produces 125 million bricks annually, through gas firing and drying processes, which contributes over 60% of Michelmersh's total carbon footprint. Working with Limpsfield Combustion, and the University of Brighton, the project partners were looking to prove the feasibility that natural gas can be replaced by hydrogen in the manufacturing process.

If this project is successful, and the hydrogen economics allow, this could provide a roadmap for reducing gas emissions by 90% across Michelmersh's manufacturing sites with further replication across the brick and wider ceramic industry.

This project was funded by the Department for Business, Energy & Industrial Strategy (BEIS) Industrial Fuel Switching Competition (Phase 1, Feasibility). The programme is part of the £1 billion Net Zero Innovation Portfolio (NZIP) which aims to provide funding for low-carbon technologies to reduce the costs of decarbonisation.

1.1 Background

Michelmersh is the fourth largest brick manufacturer in the country, and therefore has significant influence within the sector. Established in 1997, the Company has grown through acquisition and organic growth into a profitable and asset rich business.

Michelmersh strives to be a well invested, long term, sustainable and environmentally responsible business, dedicated to delivering quality products. The company has bold ambitions to decarbonise the brick manufacturing process. The overall aim of the project (Phase 1 and Phase 2) is to demonstrate the viability of replacing the natural gas used in Michelmersh's brick drying and firing processes with 100% green hydrogen.

Michelmersh has studied the various options to decarbonise their business and concluded that given the current infrastructure, and particularly for the high temperature processes, hydrogen is the most viable alternative to natural gas to deliver a step change reduction in carbon emissions.

The temperatures involved in the firing process are too high to be achieved with heat pumps and direct electric heating would also not suit the bespoke nature of the stock brick clamp-firing piles. Capturing the carbon emissions from flue gas is being conducted at the more modern sites, however it is not yet possible on the open-air clamps, used to fire the bricks at the Freshfield Lane site, which is one of the last remaining traditional clamp-fired sites in the country.

Limpsfield Combustion has a long history of burner innovation and has developed their business around this expertise over the past 25+ years. A hydrogen gas burner produced by Limpsfield was identified which could potentially provide a like for like replacement of the existing gas burners, without significant disruption or redesign of the business operation. These hydrogen burners have been in commercial operation in industrial settings in other sectors and countries for 20 years but not in the UK or in the brick manufacturing sector.

Limpsfield have also recently supplied hydrogen burners to the BEIS green distilleries Phase 1 study conducted by Locogen. This investigated the techno-economic feasibility of converting an operational distillery that uses gas oil for distillation, to one that uses hydrogen as the primary process fuel.

Whilst hydrogen burners are starting to be used in fuel switch trials in distilleries, where the burners are used to heat liquids / generate steam, there have been few trials using hydrogen burners to heat air and to fire products.

Limpsfield developed a hydrogen ready combustion burner for the Feasibility Project. This spider head design burner was specifically designed to be used in the test kiln at the Freshfield Lane site and was able to work on (i) natural gas, (ii) a blend of natural gas and hydrogen or (iii) on 100% hydrogen. It had the advantage of the same burner being able to fire the different fuels – simply requiring the gas head manifold to be changed for each fuel.

Based on Limpsfield’s previous experience from other sectors, it was expected that in addition to matching the performance of the traditional natural gas fired burner and replicate the kiln temperatures, this burner would also deliver energy efficiency savings of over 10%.

The University of Brighton is a key player in regional air quality monitoring and in the understanding of impacts of pollutants on citizens and the Earth system. UoB host a NERC AMOF community facility for atmospheric monitoring and have working collaborations with a range of key players. This project would be conducted within the UoB Centre for Earth Observation Science (CEObS), which has linkages to numerous additional, key stakeholders that have direct interest in the findings from the study, including the Chartered Institute of Building (CIOB).

1.2 Aims & Objectives

The Phase 1 (Feasibility) project was broken down into three work packages:

• WP1: Technical evaluation/ pre-feasibility of hydrogen supply to the burner at the site.

• WP2: Investigate the feasibility of retrofitting gas burners used for brick firing to use hydrogen, trialling both a 20% hydrogen blend and 100% hydrogen in a test kiln at Michelmersh’s Freshfield Lane site in Sussex.

WP2 explored burner testing to prove hydrogen firing capability and determine the overall quality impact on brick integrity and aesthetics. Data was collected and analysed to ascertain any effect to the energy efficiency of the burners, as well as the firing curve and kiln properties.

The bricks were compared against control bricks (produced using 100% natural gas) to ensure they met technical and aesthetic requirements and characteristics, with laboratory testing to ascertain their durability and structural performance.

Air quality experts from the University of Brighton monitored air quality at Michelmersh’s Freshfield Lane site. Emissions were also monitored at Limpsfield Lab.

• WP3: In parallel with the kiln testing at Freshfield Lane during Phase 1, develop and conduct lab testing of larger hydrogen ready burners, the same size as those currently used in the drying chambers at Freshfield Lane. If the Project continued to Demonstration Phase (Phase 2), this would demonstrate - at industrial scale - the effectiveness of firing hydrogen in the drying process.

1.3 Freshfield Lane

Freshfield Lane in mid-Sussex is Michelmersh Brick's second largest brick manufacturing site (see site map in the appendix). It employs traditional methods where clay bricks are fired using open air clamps using natural gas; one of only two sites left in the country offering this method. This is one of Michelmersh's more efficient production sites in terms of both number and weight of bricks produced per kWh gas.

The stand-alone kiln to be used for the trial was located in the middle of the site. This kiln was identified for the trial, as it could easily be modified, and would enable hydrogen to be trialled onsite without overly impacting on the existing manufacturing process across the site. This test kiln would replicate the firing conditions of a closed kiln firing process.

This kiln had been recently refurbished and prior to the trial was used for 'specials': one-off runs of bricks which have been specially commissioned.

Figure 1: stand-alone kiln

Figure 2: stand-alone kiln with flue

The kiln is sited in a covered metal structure which is open to two sides, thus allowing excellent ventilation. Its exhaust rises approx. 1.5m above the roof of the metal structure.

The existing natural gas burner in the kiln would be replaced by the Limpsfield hydrogen ready burner, developed especially for this trial.

2. Hydrogen Combustion

The use of hydrogen as a fuel source is well understood and has been proven in many industrial settings, however not yet in brick manufacturing. Heat is used in both the drying and firing elements of brick manufacturing. Given the direct-firing nature of the application and high temperatures required, hydrogen is an ideal low carbon energy source.

Commercial hydrogen burners and storage systems are readily available to allow the use of hydrogen as a fuel source. Green electrolytic hydrogen is also increasingly available, with an expected price to be achieved in the next 5 -10 years to be significantly lower than that of blue hydrogen (owing to the high cost of natural gas and the additional CCUS processes required). The different components required to construct the engineering solution for the project can be procured, constructed and installed with relative ease.

Hydrogen combustion results in water vapour without any carbon emissions. However, hydrogen's wide flammability limits require consideration in safety assessments, and its higher flame speed compared to natural gas increases the flame temperature locally, potentially generating high levels of NO_x. As part of the project, the University of Brighton carried out Air Quality monitoring at the Freshfield Lane site.

2.1 Fuel Switching to Hydrogen: Reduction in Carbon Emissions

This project will trial replacing gas with green hydrogen produced using renewable power. Assuming an average 3gCO_2e/MJ for production of the green hydrogen, and 5gCO_2e/MJ for downstream distribution emissions, this would result in overall lifecycle GHG emissions of green hydrogen to be 8gCO_2e/MJ (29 gCO_2e/kWh). By 2030 this is expected to decrease to <5gCO_2e/MJ (18gCO_2e/kWh), mainly due to the decarbonisation of UK grid electricity.

Using hydrogen would therefore reduce carbon emissions by 85- 90% compared to when using natural gas, which has a carbon intensity of 51gCO_2e/MJ (180gCO_2e/kWh).

If this study is successful, fuel switching from natural gas to hydrogen could be replicated across the brick fired manufacturing sector, and indeed across the wider ceramics industry.

Whilst hydrogen burners are starting to be used in fuel switch trials in distilleries (as seen in the Green Distilleries Phase 2 trials), where the burners are used to heat liquids / generate steam, there have been very few trials using hydrogen burners to heat air and to fire products. This trial is therefore a ground-breaking trial (possibly a world first using hydrogen onsite in bricks manufacture). It has the potential to lead to wider carbon savings not only across the across the brick manufacturing sector, but also across the wider ceramic sector, and potentially wider across other manufacturing industry, wherever burners are used to heat air and to fire products.

A route map for decarbonising the brick industry would also be of enormous international importance, especially for India where about 250 billion bricks are manufactured annually, using similar traditional methods to those used at Freshfield Lane.

Further replication of this technology to other manufacturing processes would make a significant contribution to UK climate change commitments.

2.2 Hydrogen Burners

Limpsfield Combustion has a long history of developing hydrogen burners, with the first burner tested in the U.S. over 20 years ago. Hydrogen burners are therefore already available on the market in the UK and are designed, tested and manufactured at their facilities. Each new project requires specific adaptations to the design.

Figure 3: Limpsfield burner

Figure 4: Hydrogen burner undergoing test firing with hydrogen in Limpsfield Lab

Hydrogen burners have significant application beyond brick manufacturing, and following a successful project, Limpsfield would be in a position to target other industries that use gas for heat or steam production e.g. ceramics, food production, pharmaceutical / chemicals companies, automotive etc. for further expansion.

Hydrogen firing creates a challenge for the burner, gas train and flame sensing equipment as it is 14 times lighter than air. In daylight the flame is invisible, and it has a completely different flame speed compared to natural gas, or other gaseous fuels such as LPG.

3. WP1: Pre-Feasibility Report

The Pre-Feasibility report identified the hydrogen standards, infrastructure, safety and other requirements / considerations that needed to be met for the successful deployment of hydrogen onsite. The hydrogen ready burner would be connected to a dedicated hydrogen supply via a depressurisation skid – and would not be connected to natural gas. At the end of the trial, the pipework would be disconnected, and the gas train on the burner would be reconnected to natural gas. This would enable the kiln to continue to be used to fire specials once the trial was completed. There would be no disruption to business-as-usual operations following the trial.

The report raised issues around the blended trials:

- Whether to continue with the blended trials, due to the increased complexity of blending the gases onsite, together with the additional costs of the blending equipment (not included in the original budget) – the need for which has been highlighted in this report.
  A system of 100% hydrogen with no blending of gases would be a simpler system to design, assemble, test, install, commission and monitor.

3.1 Hydrogen Blend

The original project aims included trialling burning a blend of gas (20% hydrogen, 80% natural gas), in addition to the 100% hydrogen burns. The proposal was to blend gas onsite, at point of use.

The Energy Networks Association and other gas network organisations have been proposing utilising a blend of 20% hydrogen with natural gas in the existing gas infrastructure, in order to help support the transition to a net zero future. Blending hydrogen would be a transitional step from the current natural gas economy to a future hydrogen economy. The HyDeploy project found that consumers can safely receive up to 20% hydrogen blended with natural gas without need to make any changes to their existing appliances.

However, the Pre-Feasibility report found that blending gas onsite at point of use would require the following engineering considerations:

- Ensuring that the gases are well mixed;
- Ensuring that the mixture ratio (and therefore the calorific value (CV) of the gas) remains constant;
- Ensuring that the oxygen intake matched the calorific value (CV) of the blended gas at the point of combustion,
- Detection mechanisms for circumstances that cause the CV / blend % to change – e.g. pipe blockage, or not enough pressure from one of the gases.

Following an options appraisal, the Project Team decided to focus on the 100% hydrogen trial burns and descope the blended hydrogen trials due to:

- increased complexity of the delivery rig if onsite blending were to take place (and its potential impact on lead-in time),
- additional safety issues ensuring that the blended gases are well mixed,
- increased costs not included in the HyBricks budget.

The Project Team agreed that a system of 100% hydrogen with no blending of gases would be a simpler system to design, assemble, test, install, commission and monitor. By de-scoping the blended trials the consortium could focus on the delivery of the highest carbon reduction process.

4. Project Design

4.1 Limpsfield Burner and Gas Train

As part of the project, Limpsfield developed a spider head design burner capable of firing natural gas, hydrogen, and a blend of the two gases. This enabled the existing burner in the kiln to be replaced with the Limpsfield hydrogen-ready burner. The burner could then be used to fire the control bricks using natural gas and then both the 20% hydrogen blend and 100% hydrogen trials. This had the advantage of the same burner being able to fire the different fuels – simply requiring the gas head manifold to be changed for each fuel.

The hydrogen supply pressure at the inlet to the gas train of the Limpsfield burner was 3 bar (at between 18-20°C). The burner comes with its own pressure regulator in the gas train to regulate from 3 bar down to 350/300 mbar. The approx. pressure drop through the gas train (reg valve, 2 x safety valves) to the burner is 150 to 200 mbar. Hydrogen at the burner is assumed to be at 100 mbar.

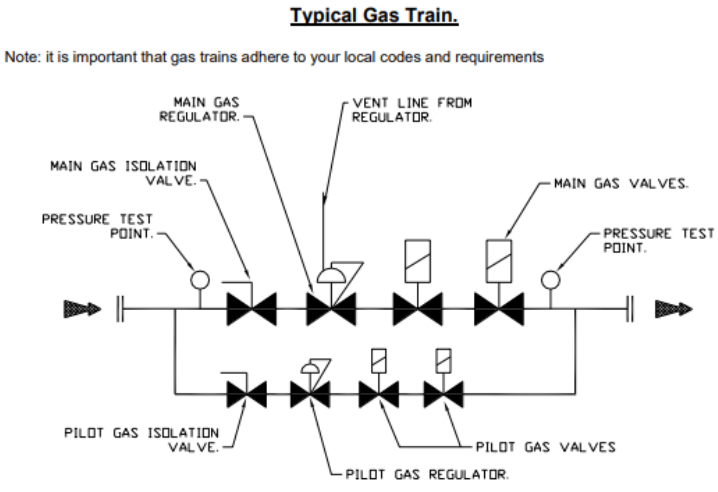


Figure 19: Schematic of a typical gas train (LP1 & LP2)

Figure 5: Typical Gas Train

The hydrogen ready burner was connected to a dedicated hydrogen supply via a depressurisation skid – and was not connected to natural gas. At the end of the HyBricks trial, the pipework was disconnected, and the gas train on the burner was reconnected to natural gas. This enabled the kiln to continue to fire specials once the trial was completed, ensuring that there was no disruption to business as usual operations following the trial.

4.2 Hydrogen Pressure Reducing System (the 'Skid')

Gas pressure reducing skids are packaged stations, pre-assembled on a steel structure, designed to provide gas at the required pressure.

FT Pipeline Systems designed, fabricated, assembled, installed and commissioned the hydrogen pressure reducing system (the 'Skid'). The dedicated hydrogen supply stored at 300bar in the MCPs was reduced to 3bar at the inlet to the gas train. This was a 2-stage pressure reduction – the first stage reduced pressure from 300bar to 5 bar, with the second stage reducing further to 3bar.

Site Ambient Conditions

Max ambient temperatures: 31°C
Min ambient temperatures 6°C

<u>Design Conditions</u>

Hydrogen Gas
Inlet Pressure 300 bar
Outlet pressure 3 bar
Maximum Flow 86Nm3/H

See appendix for detailed design of the skid.

Figure 6: Hydrogen Pressure Reducing Skid

4.3 Hydrogen Storage & Delivery

GeoPura were responsible for supplying the green hydrogen to site. Due to the volumes of hydrogen required, the most efficient solution was to deliver the hydrogen at 300 bar, either in fork-liftable MCPs (Manifold Cylinder Packs) or bulk MEGC (multiple element gas containers) tube trailers as appropriate.

Figure 7: Fork-liftable MCP of hydrogen in the Limpsfield Lab

During the trial, GeoPura supplied hydrogen in MCPs. Each MCP contained 17kg of hydrogen at 300bar. 16 MCPs were supplied in total.

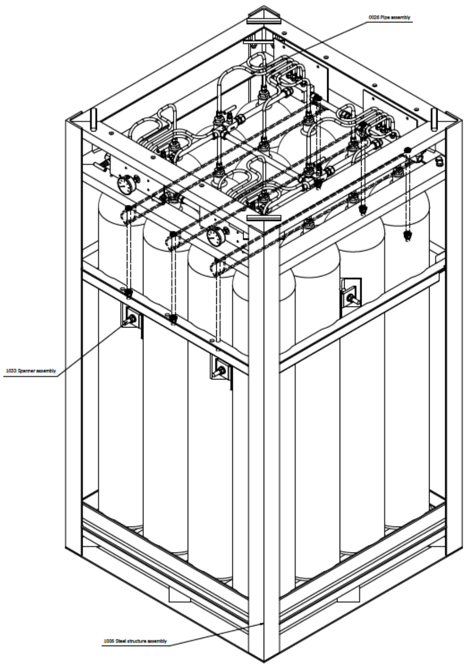


Figure 8:Hydrogen Manifold Cylinder Pack (MCP)

Figure 9: Hydrogen MCPs onsite

4.4 Mass Flow Meter

In order to accurately record the amount of fuel (both natural gas and hydrogen) that was used for firing the bricks, a Mass Flow Meter was installed which could accurately measure both natural gas and hydrogen. This allowed both the natural gas and hydrogen required for firing the bricks to be measured with a high level of precision.

The Fox Thermal Gas Mass Flow Meter (below) was found to be a suitable meter for the project, and was pre-calibrated for both natural gas and hydrogen.

Figure 10: Fox Thermal Flow Meter behind kiln

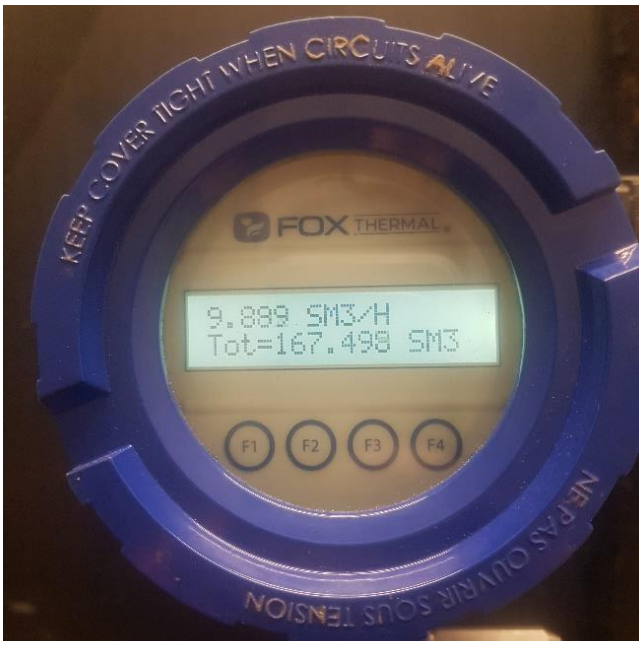


Figure 11: Close up of Fox Thermal Flow Meter

5. Health and Safety

5.1 Hydrogen Standards

The following standards were identified which needed to be complied with:

BCGA Code of Practice (CP) 33 The Bulk Storage of Gaseous Hydrogen at Users' Premises (Revision 1: 2012)
BCGA GN-13 DSEAR Risk Assessment (2021)
BOC Safety Distances for Bulk Gaseous Hydrogen (2015)
BOC Safety Data Sheet Hydrogen, Compressed (Version: 1.6, 2020)
BS EN 1127-1:2019. Explosive atmospheres. Explosion prevention and protection
DSEAR (Dangerous Substances and Explosive Atmosphere Regulations) (2002)
DSEAR Approved Code of Practice and guidance (L138, second edition, 2013)
European Council Directive 1999/92/EC Potentially Explosive Atmospheres 'ATEX '
European Council Nonbinding Guide to Good Practice for Implementing the Directive 1999/92/EC 'ATEX' Explosive Atmospheres (2005)
FCH Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) Safety Planning and Management in EU Hydrogen and Fuel Cells Projects – Guidance Document
IGEM/H/1 Reference Standard for low pressure hydrogen utilisation (2021)
IGEM/SR/25 – Hazardous area classification of Natural Gas Installations (Edition 2, 2010)
ISO/TR 15916:2015 Basic Considerations for the Safety of Hydrogen Systems (Edition 2, 2015)

5.2 Location of MEGC Trailer and Skid

In line with BCGA Code of Practice (CP)33 The Bulk Storage of Gaseous Hydrogen (2012) (see below from BOC: CES/TD009/508310/0815), the following distances needed to be maintained when assessing the potential locations for the hydrogen cylinders and the skid.

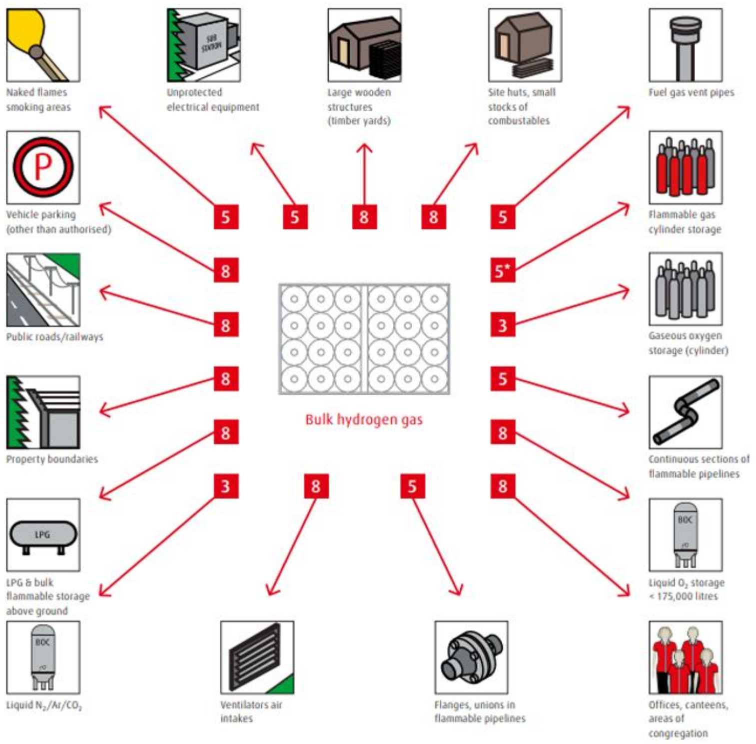


Figure 12: Minimum recommended horizontal distances for hydrogen bulk gas systems (distance in metres)

5.3 DSEAR Assessment

The Pre-Feasibility report highlighted that the kiln needed to undergo an assessment under DSEAR (Dangerous Substances and Explosive Atmosphere Regulations) 2002.

The DSEAR report concluded that:

- The Atmosphères Explosible (ATEX) zones identified could be accommodated within the area of the east bay. However, the system specific position and layout within the east bay could be optimised to mitigate fire and explosions risks for this temporary installation.
- The gas train elements within the Kiln Building result in a Zone 2 of Negligible Extent (NE).

The DSEAR report recommended that:

- The hydrogen containers and Pressure Reducing Skid should be wholly located within the east bay, and not projecting out beyond the mouth of the bay.
- The hydrogen and Skid should be located nearer the concrete walls in the bay, ensuring 3m is kept between the hydrogen / skid and the concrete walls, in line with the BCGA CoP 33 guidance.
- A Heras fence should be established across the mouth of the east bay once the hydrogen and skid are in place, with two access points on opposite sides of the bay to allow for escape / access routes in the event of a fire. Appropriate signage should be on the Heras fencing to ensure personnel entering the bay are aware of the presence of ATEX zones, and restrictions on introducing ignition sources.
- Site emergency plans should ensure that the presence of the hydrogen system is considered, so that operator actions in the event of other emergencies at site are appropriate to leave system in a safe state and that site personnel are aware of potential behaviour of the hydrogen system including visual/audible alarms and pressure relief venting.
- Offsite first responders should be properly briefed to ensure:
    - They are fully aware of the system, and it functions, including location of pressure indication and shut off valves.
    - Are fully aware of potential responses they will need to take at site such as cooling/wetting jet fire impinged equipment or flammable items such as the wooden barrier between the east and west bays.

5.4 HAZOP Assessment

A HAZOP Assessment was also carried out which covered the following main system elements:

▪ Pressure reduction skid – containing both the main hydrogen store and initial pressure reduction from the storage pressure
▪ Burner supply system – hydrogen isolation and flow control elements, including necessary additional pressure reduction into the hydrogen burner
▪ Brick kiln – current brick kiln with additional connections to accommodate hydrogen supply
▪ Safety and monitoring systems – hydrogen detection and alarming/alerting systems

The HAZOP study provided a structured and analytical approach to hazard identification. HAZOPs are a systematic analytical hazard identification processes, utilising a structured multi-disciplinary brainstorming approach carried out on a process design to identify the hazards and operational issues associated with the site or operation of the process.

5.5 Training

The burn was monitored throughout, with staff onsite 24/7. All staff who were working with or around hydrogen needed to be adequately trained on hydrogen safety procedures including:

- Hydrogen properties and behaviour
- Safety requirements for working with or around hydrogen
- Hydrogen equipment inspection, operation, and maintenance
- Safety requirements for handling gas under high pressure if appropriate
- Emergency notification and evacuation/response policies and procedures
- First aid procedures

5.6 Procedures

Hydrogen specific procedures were required for the project, including the following:

- Operating procedures that describe the operating steps for the system, apparatus, and equipment in a facility.
- Safe work practices used to control hazards during operations such as lockout; confined space entry; opening equipment or piping; and control over entrance into a facility by maintenance, contractor, laboratory, or other support personnel.
- Management of change procedures that describe the method that will be used to review proposed changes to materials, technology, equipment, procedures, personnel and facility operation for their effect on safety vulnerabilities.
- "Stop Work" procedures establish the authority and responsibility, without reprisal, for workers to stop work when they discover that employees are exposed to conditions of imminent danger or to other hazards (e.g., leaking valves in a hydrogen system).
- Clear decision and communication chains for reacting to safety concerns/incidents, including formal approval to resume operations after issue has been addressed.
- Emergency response procedures for onsite personnel to ensure employee safety during an emergency situation at the facility.
- Offsite first responders to be briefed to ensure they are fully aware of the system, and potential responses they would need to take at site in the event of an emergency.

5.7 Detection Equipment

Following assessment of the site and taking into account the hydrogen pressure reduction system design, it was recommended that the following detection equipment should be used onsite to ensure 3 layers of leak, gas and flame detection.

- 1 x SearchZone Sonic Ultrasonic Leak Detector
- 4 x MeshGard H_2 ppm Gas Monitors (magnetic mount)
- 2 x FS20X Flame Detector (Tower Mount with Beacon and Sounder System)
- 1 x TouchPoint Plus Control Panel

Following the HAZOP, it was agreed that the control panel for the detection equipment be connected to the skid (via pneumatic controls) so that the detection equipment could remotely activate the slam shut valves on the skid.

The UltraSonic Leak Detector needed to be onsite at least a week before works commenced so that the sensors could calibrate to ambient conditions, whereby they take a baseline reading of the ultrasonic activity (noise, vibrations, etc) onsite.

6. WP2: Burner Trials: Firing Bricks

6.1 Burning Profile

In order to carry out a successful burn and for the bricks to achieve the required structural integrity and aesthetic properties, Michelmersh's usual burning profile below would need to be achieved throughout the kiln (including within the centre of the brick stack). This involves slowly ramping up the temperature, holding it at top temperature for a number of hours, and then gently ramping down again.

6.2 Burner Testing – Impact on Brick Integrity

The overall aim of WP2 was to explore burner testing to prove hydrogen firing capability and determine the overall quality impact on brick integrity and aesthetics.

The Limpsfield hydrogen-ready burner therefore needed to be able to produce bricks with the required structural integrity when firing both with natural gas and later with hydrogen.

6.2.1 Required Characteristics

The design strength of bricks should comply with BS EN 1996-1. Clay bricks have to meet specific criteria.

For one and two storey homes, clay bricks to BS EN 771, with a minimum compressive strength of 9N/mm^2 should be adequate. For three storey homes; clay bricks to BS EN 771 with a minimum compressive strength of 13N/mm^2 are acceptable[1].

The most widely used work size for UK clay bricks is 215 x 102.5 x 65mm.

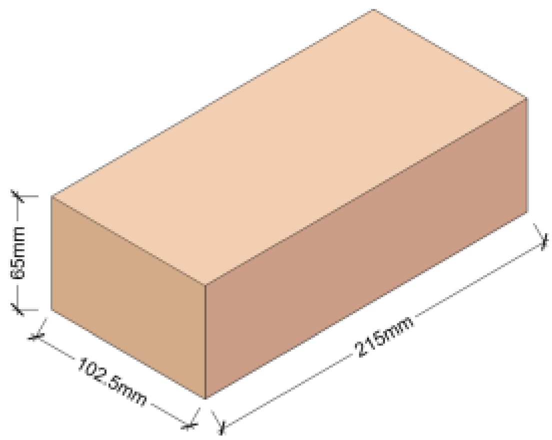


Figure 13: The most widely used work size for UK Clay bricks

The tolerance is the difference between the stated work size and the average actual size. The tolerance is stated as T2 (generally the smallest deviation from the stated work size), T1 or Tm (deviation in mm from the stated work size declared by the manufacturer; it may be wider or closer than the other categories).

[1] NHBC Standards 2022

Declared Size [mm]	T2 Lower & upper limits [mm]	T2 Tolerances [mm]	T1 Lower & upper limits [mm]	T1 Tolerances [mm]	Tm
215	211-219	±4	209-221	±6	As declared by the manufacturer
102.5	99-105	±3	98-106	±4	
65	63-67	±2	62-68	±3	

Table 1: T2, T1 and Tm tolerance limits for standard sized UK clay bricks

The range value covers the dimension difference within a sample, between the largest brick and the smallest. The range will be stated as R2 (generally the smallest range), R1 or Rm (range in mm declared by the manufacturer; it may be wider or closer than the other categories).

The Freshfield Lane bricks produced during the trial were *First Quality Multi* bricks, clamp-fired stock facing bricks.

MICHELMERSH
Britain's Brick Specialists

Product Technical Information Sheet

Freshfield Lane
First Quality Multi

Configuration:	Frogged Clay Facing Brick				
Size:	215 x 102.5 x 65 mm				
Dimensional Tolerance:	T2		Dimensional Range:	R1	
Density (net):	1690	Kg/m³	Density Tolerance:	D1	
Density (gross):	1460	Kg/m³			
Compressive Strength:	27	N/mm²	Compressive Strength Category:	II	
Water Absorption:	12	%	Initial Rate of Water Absorption:	2.5	
Durability Category:	F2		Soluble Salts Category:	S2	
Thermal Conductivity: (P=50)	0.45	W/m.K	Thermal Resistance P=50:	0.23	m².K/W
Thermal Conductivity: (P=90)	0.51	W/m.K	Thermal Resistance P=90:	0.20	m².K/W
Water Vapour Permeability Coefficient:	5/10		Bond Strength (fixed value):	0.15	N/mm²
Dangerous Substances:	Not Applicable		Void Percentage:	6 - 11	%
Recycled Content:	0	%	Reaction to Fire:	Class A1	

Clay bricks are manufactured and supplied to relevant clauses of BS EN 771-1.

Figure 14: Product Technical Information Sheet for Michelmersh's First Quality Multi Bricks

If the bricks were to be acceptable as Michelmersh's *First Quality Multi*, as well as meeting the aesthetic and structural requirements and characteristics, the bricks therefore had to achieve the following:

- dimensional tolerance T2: 211-219mm x 99-105mm x 63-67mm
- water absorption ≤ 12%
- compressive strength 27 N/mm^2.

6.3 Natural Gas Burner Trials

A key stage of WP2 was to install the Limpsfield hydrogen-ready burner in the stand-alone kiln and to fire it using natural gas. This was carried out, following some initial interoperability issues between the burner controls and the kiln controls. The aim was for the Limpsfield hydrogen-ready burner to be able to fully replicate the burns achieved with Michelmersh's previous burner, so that following the hydrogen trial it could be used to fire 'specials' in the kiln.

However, the requirements of the brick burn were more demanding than had been expected and additional modifications to the burner / firing cycle were needed to fully fire the bricks and achieve the required structural integrity.

6.3.1 Old Burner: Prior to Installation of Limpsfield Burner (Natural Gas)

A reference burn took place using Michelmersh's existing burner (prior to the installation of the Limpsfield burner). This followed the burning profile as outlined previously, although it should be noted that following the 'soak' at top temperature, the temperature dropped more rapidly than the set points.

6.3.2 Limpsfield Hydrogen-Ready Burner Trials (Natural Gas)

A number of trial natural gas burns then took place using the Limpsfield hydrogen-ready burner (3 burns were also unfortunately aborted due to power outages or motor failure). When firing natural gas, the Limpsfield hydrogen-ready burner successfully followed the required burning profile:

- when ramping up the temperature
- holding the top temperature for a number of hours (the 'soak').

However, in the early trials, although the required temperature was achieved in the ambient air of the kiln, the temperature in the middle of the brick stack did not reach the required temperature, and therefore the bricks were not sufficiently fired.

As a result, additional trials took place, with the following variations:

- additional thermocouples inside the kiln to monitor the temperatures achieved inside the brick stack
- increasing the air from below 1% to 3%
- raising the top temperature
- increasing the length of soak at top temperature by up to 4 hours.

The natural gas consumption was recorded during the old burner reference burn and with each trial of the new burner. The initial burns (Trials 2 - 6) which all followed the same burning profile / set points all reduced gas consumption by 24% or more.

As the burns were modified to correctly fire the bricks, the gas consumption increased somewhat. The final natural gas burns (Trials 8, 9, 10) varied the firing curve parameters in order to achieve the required structural integrity. These three trials increased the maximum temperature, extended the 'soak' time, and supplied more air to the kiln, and as a result, increasing the total gas consumption.

6.3.2.1 Brick Appearance and Structural Testing

The initial burns (Trials 1-7) were within the dimensional tolerances, but failed the water absorption tests as they absorbed more than 12% water by weight.

The final natural gas burns (Trials 8, 9, 10) increased the maximum temperature and extended the 'soak' time. Trial 10 also supplied more air to the kiln to increase oxygen levels during combustion. These absorbed less water, and therefore passed the water absorption test. However, the bricks in Trial 9 displayed some bloating, and therefore failed the dimensional tolerances. Trial 10 passed both the dimensional and water absorption tests.

6.3.3 Findings from Natural Gas Trials

The unexpected challenges around burner controls which were encountered highlighted the following learning points for future trials:

- the importance of ensuring early communications between all parties involved in kiln / burner controls,
- the need to time any burner replacements – preferably to combine with pre-planned maintenance or periods of low demand to mitigate the disruption on the production cycle,
- natural gas trials proved more complex than expected, but these provided invaluable learning opportunity for Michelmersh and Limpsfield to modify the burner controls and the burn cycle to achieve the required conditions for the final product.

6.4 Hydrogen Burner Trials

Following the completion of the natural gas trials, the kiln was completely disconnected from the natural gas supply. The hydrogen pressure reducing skid was installed by FT Pipeline Systems, with a new dedicated pipework to the burner.

The safety monitoring equipment was installed and calibrated onsite. The safety monitoring control panel was connected to the skid (via pneumatic controls) so that the detection equipment could remotely activate the slam shut valves on the skid.

The hydrogen was delivered to site in 16 MCPs. Following extensive onsite training, the skid was gradually brought up to 300bar for the trial hydrogen burns to take place. The gas head manifold on the burner was swapped over to a hydrogen manifold and was recommissioned.

An experienced hydrogen engineer from FT Pipeline Systems oversaw all 3 hydrogen burns.

Following the results of the natural gas trials, it was determined to use the burning profile from the later natural gas trials (Trials 8-10), with a higher top temperature and an extended soak. Air intake was also kept at 3%.

6.4.1 Hydrogen Burn 1

The first hydrogen burn experienced repeated pressure drops in the hydrogen supply. The skid pressure kept dropping, causing the slam shuts to operate and the burner light to go out. As a result, the actual temperature dropped below the set point during the later stages of the ramping up period and the first part of the high temperature soak.

The time lost was not enough to abandon the firing. The rest of the burn took place without any issues. Note that as previously with the natural gas burns, following the 'soak' at top temperature, the temperature initially dropped more rapidly than the set points.

6.4.2 Hydrogen Burn 2

The second hydrogen burn did not experience the same pressurisation issues as Hydrogen Burn 1. However, the programme was lost overnight when it should have been ramping up to, and holding top temperature, and this was not rectified for a number of hours. As a result, the kiln temperature dropped substantially over a period of 7 hours. This was eventually rectified, and the programme was adjusted to bring the temperature back up. The rest of the burn took place without any issues.

It was noted that hydrogen managed to bring the temperature back up far quicker than natural gas would have done – this burn would likely have not been salvageable with natural gas.

6.4.3 Hydrogen Burn 3

The firing for the third hydrogen burn was completed from start to finish with no interruptions. No issues were observed; the burn successfully followed the set points whilst the temperature was ramping up and during the soak at top temperature. Again, the temperature dropped more rapidly than the set points in the cooling period.

6.5 Hydrogen Burns – Brick Appearance and Structural Characteristics

6.5.1 Hydrogen Burn 1

Burn 1 resulted in a completed burn with brick quality being bloated and exhibiting some cracking, and a reasonable colour range across the firing.

The bricks were subject to Michelmersh's internal structural testing. Water absorption was 11% (and therefore met the absorbency requirements), but all Burn 1 bricks were found to be oversized.

Hydrogen Kiln Test No 1

Figure 15: Hydrogen Burn 1 Bricks in Kiln

Figure 16: Hydrogen Burn 1 Test Panel

6.5.2 Hydrogen Burn 2

Burn 2 resulted in complete burn; brick quality was improved upon burn 1, with less cracking, and a good colour range across the firing. Product structural characteristics upon inspection showed good results; water absorption was an acceptable 12%, and product sizing was better than burn 1 with some bricks falling within tolerance. However, 60% of the bricks tested were still oversized.

Figure 17: Hydrogen Burn 2 Bricks in Kiln

Figure 18: Hydrogen Burn 2 Test Panel

6.5.3 Hydrogen Burn 3

Although burn 3 firing was completed from start to finish with no interruptions, overall results were very similar to burn 1. Brick quality was again bloated and displayed cracking, although there was a reasonable colour range across the firing. Water absorption at 11% was within the required parameters, but again the bricks were found to be oversized.

Figure 19: Hydrogen Burn 3 Bricks in Kiln

Figure 20: Hydrogen Trial 3 Test Panel

6.6 Independent Structural Testing

The bricks from Hydrogen Burn 1 were also submitted to Lucideon for independent structural testing. Lucideon is a UKAS accredited testing and calibration laboratory in the UK, and is a Notified Body (NB 1289) under the Construction Products Regulation (EU) 305/2011 for the assessment and verification of construction products. Lucideon maintains impartial procedures for all work performed as a Notified Body to safeguard its independence.

6.6.1 Compressive Strength

The compressive strength of Hydrogen Burn 1 bricks was found to be between 14.9 – 23.2N/mm^2. Although this is lower than the technical requirements of *First Quality Multi* bricks (27N/mm^2), this still is well within BS EN 771, which requires a minimum compressive strength of 9N/mm^2 for one and two storey homes, and 13N/mm^2 for three storey homes.

6.6.2 Dimensional Tolerance

Lucideon found that the Hydrogen Burn 1 bricks were within Dimensional Tolerance T1 (±6mm), rather than T2 (±4mm). Again, this was an acceptable range, even if it did not meet Michelmersh's objective to achieve the same technical specifications as *First Quality Multi* bricks which are T2.

6.6.3 Water Absorption

Lucideon found the water absorption to be an average of 14%. Again, although it did not achieve the same technical specifications as *First Quality Multi* (≤12%), the water absorbency achieved is still acceptable in clay bricks. Indeed, Michelmersh's own *Hampshire Stock Light Multi* has a water absorption of ≤18% (see appendix).

6.7 Energy Consumption

The hydrogen consumption during the trials was monitored with the Fox thermal flow meter. The burn profile in the three hydrogen burns attempted to follow the burn profile from NG Trial 10, namely 15 hours soak with increased oxygen levels. Only H_2 Trial 3 successfully followed this burn profile in both the ramping up and high temperature soak stages.

When following this burn profile, Hydrogen Trial 3 consumed 10% less energy than that used in NG Trial 10. Unexpectedly, Hydrogen Trial 2 produced more successful bricks, even though the burn profile was not successfully followed. H_2 Trial 2 consumed 24% less energy than NG Trial 10, and only 3% more energy than the original NG burner.

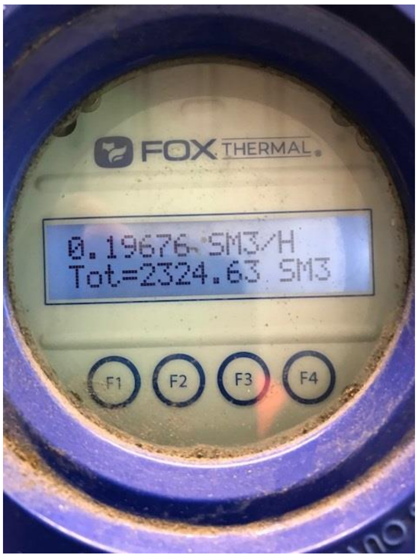


Figure 21: Close up of Fox Thermal Flow Meter (H_2 reading)

7. Air Quality Monitoring

7.1 Background Emissions (July 2022)

During July 2022, prior to the start of the hydrogen trials, background emissions of NO_2, SO_2 and H_2S were assessed across the site using diffusion tubes.

39 diffusion tubes were deployed across the site and exposed for three weeks to assess background concentration of NO_2, SO_2 and H_2S. Concentration data was successfully attained from 38 diffusion tubes, with 30 of these seeing concentrations above the limit of detection once laboratory blank correction was applied.

Table 2: The number of diffusion tubes deployed, analyses and at the reporting level for the site

POLLUTANT	TUBES DEPLOYED	TUBES ANALYSED	TUBES ABOVE DETECTION LIMIT
NO_2	14	14	14
SO_2	15	14	14
H_2S	10	10	2

Concentrations of NO_2 varied across the site but remained within objective values (assuming extrapolation of the averaging and measurement time) specified by the Air Quality Standards Regulations 2010 (range: 1.5 – 22.7 µg m^{-3}). Unsurprisingly, NO_2 concentrations were highest in areas likely to see the highest vehicle movements, e.g. by the fuel pumps and the loading area. These data suggest that the overall background concentrations of NO_2 here are relatively low for an industrial location.

As with NO_2, measured SO_2 concentration varied across the site. No tubes measured background concentrations that exceeded objective values (assuming extrapolation of the averaging and measurement time) defined by the Air Quality Standards Regulations 2010 (range: 6.5 – 89.2 µg m^{-3}). Concentrations were highest around the clamps, although such a finding would be expected given the nature of the work undertaken on site. SO_2 concentrations were notably lower along the south-eastern boundary of the site.

Concentrations of H_2S were consistently low across the entire site, and well below the concentrations at which H_2S is shown to be dangerous to human health (range: 0.1 – 0.4 µg m^{-3}). The highest concentration recorded (0.4 µg m^{-3}) would equate to roughly 280 ppt, whereas H_2S is only shown to become damaging to health where concentrations of 10 ppm or greater are present (Doujaiji & Al-Tawfiq, 2010).

Where substances have been classified as carcinogens, mutagens or asthmagens, Michelmersh complies with the Control of Substances Hazardous to Health regulations 2002 (COSHH), controlling exposure to as low as is reasonably practicable. Michelmersh continuously works to achieve and maintain WEL (Workplace Exposure Limits) within EH40.

7.2 Hydrogen Burns - Emissions Assessment

7.2.1 Sampling Methodology

A Serinus S50 Sulphur Dioxide Analyser (S50), a Serinus S40 Oxides of Nitrogen Analyser (S40) and a Los Gatos Ultra-Portable Greenhouse Gas Analyser (UGGA) (Model 915-0011) were deployed to assess combustion emissions, with the various detection limits given in Table 3.

The sample inlet was positioned just beyond the kiln stack and therefore allowed for some dilution in ambient air. A mixing chamber was utilised to help dilute and cool the sample via diffusion, with the flow rates of each line given in Figure 22. The UGGA makes use of an internal pump, whilst the S50 and S40 used an external pump. A third external pump was deployed to ensure a sufficient vacuum was present within the mixing chamber to pull the flue sample along approx. 5 metres of stainless-steel tubing. The exhaust lines of the three pumps and UGGA fed into a second mixing chamber, with a large gauge line feeding the total exhaust outside. Pollutant concentrations were scaled up by ~44% to account for the dilution.

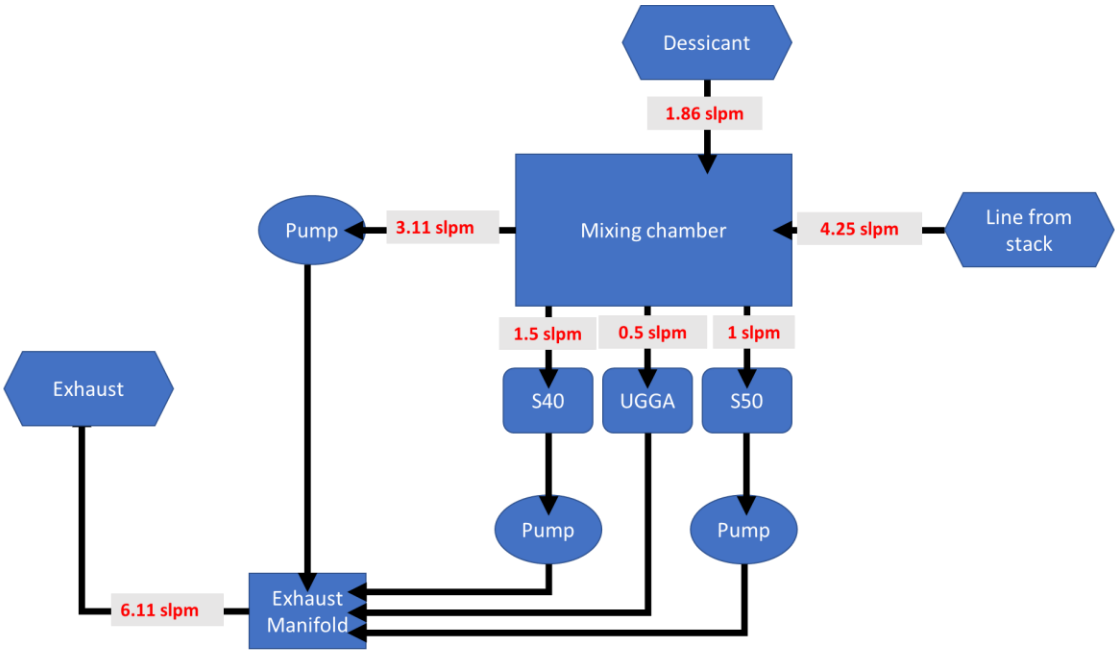


Figure 22: Diagram of sampling set up and flow rates (arrows indicate direction of flow)

TRACE GAS	INSTRUMENT	LIMITS	PRECISION
CH_4 **CO_2** **H_2O**	Los Gatos UGGA	0.01 to 100 ppm 1 to 20,000 ppm 500 to 70,000 ppm	2 ppb 300 ppb 200 ppm
NO **NO_2** **NO_X**	Serinus S40	0 to 20,000 ppb USEPA designation: 0 to 500 ppb MCERTS EN certified range (NO): 0 to 1,000 ppb MCERTS EN certified range (NO_2): 0 to 260 ppb	Greater of 0.4 ppb or 0.5% of reading
SO_2	Serinus S50	0 to 20,000 ppb USEPA designation: 0 to 500 ppb MCERTS EN certified range: 0 to 400 ppb	Greater of 0.5 ppb or 0.15% of reading

Table 3: Instruments used and their limits

7.2.2 Secondary Background Assessment (November 2022)

As the emissions sampling set-up was kept operational where the kiln was not being fired, a secondary background assessment was undertaken. This provides a reflection of concentrations in November 2022, rather than July 2022, with higher precision instruments than the diffusion tubes deployed previously.

The data collected is shown in Figure 23, with the three individual burns easily discernible. Outside of kiln firing times, it is clear from Figure 23 that all pollutant concentrations (apart from H_2O) remained fairly low and consistent, although the CO_2 background did see a slight increase following the conclusion of Burn Two. Given the sampling was undertaken outside, it is expected that water content within the air would vary in line with weather conditions. The concentrations recorded during background operations are comfortably within the limits specified by the Air Quality Standards Regulations 2010.

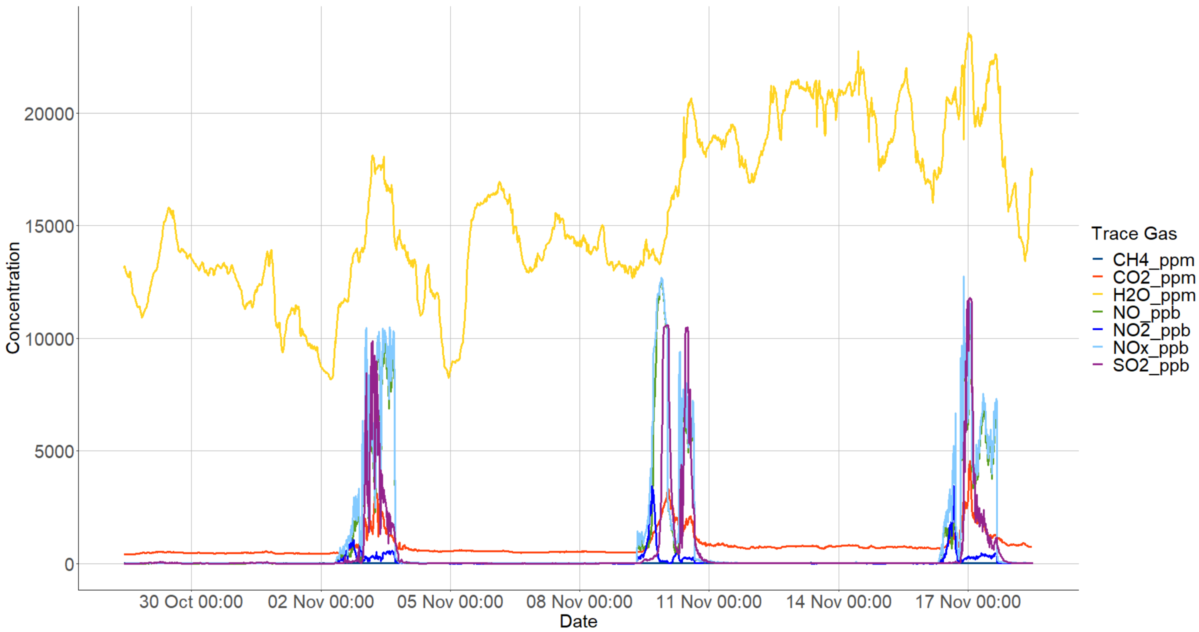


Figure 23: Emissions profile throughout study period

TRACE GAS	MEAN (UNITS GIVEN)	MEAN (µg/m³)	LIMIT (µg/m³)
CH_4	2.9 ppm	1.9	N/A
CO_2	581.9 ppm	1,047.382	N/A
H_2O	15,144.2 ppm	11,161.5	N/A
NO	4.0 ppb	7.7	N/A
NO_2	2.8 ppb	5.4	40 (annual mean)
NO_X	6.8 ppb	13.0	30 (annual mean)
SO_2	6.6 ppb	17.6	125 (annual mean)

Table 4: Mean background concentrations recorded by the emissions monitoring equipment, and the relevant legal standard

7.2.3 Burns Overview

Three hydrogen fired cycles were successfully measured over a three-week period, from November 2nd, 2022, to November 18th, 2022. Three instrument outages occurred during background measurements following power outages, however these did not impact the collection of data throughout the burning cycles themselves.

Burn One was characterised by a drop in hydrogen pressure during the initial period where the temperature was ramping up, which delayed the time at which the kiln reached peak temperature. Burn Two saw the burner lose its programme for a short duration nearing the conclusion of the "soak" stage, which resulted in a loss of temperature that was reacquired later in the cycle. Burn Three saw the cycle complete as planned. The achieved temperatures and emissions timelines of all three burns, along with the average burn, are given in Figure 24 (a to d). A Natural Gas burn was monitored as part of this study, with a profile given in Figure 29, although kiln temperature is not shown as this data was not available at the time of writing.

For this assessment, the burn was considered to have completed when pollutant concentrations had returned to background levels, rather than when the kiln had cooled completely.

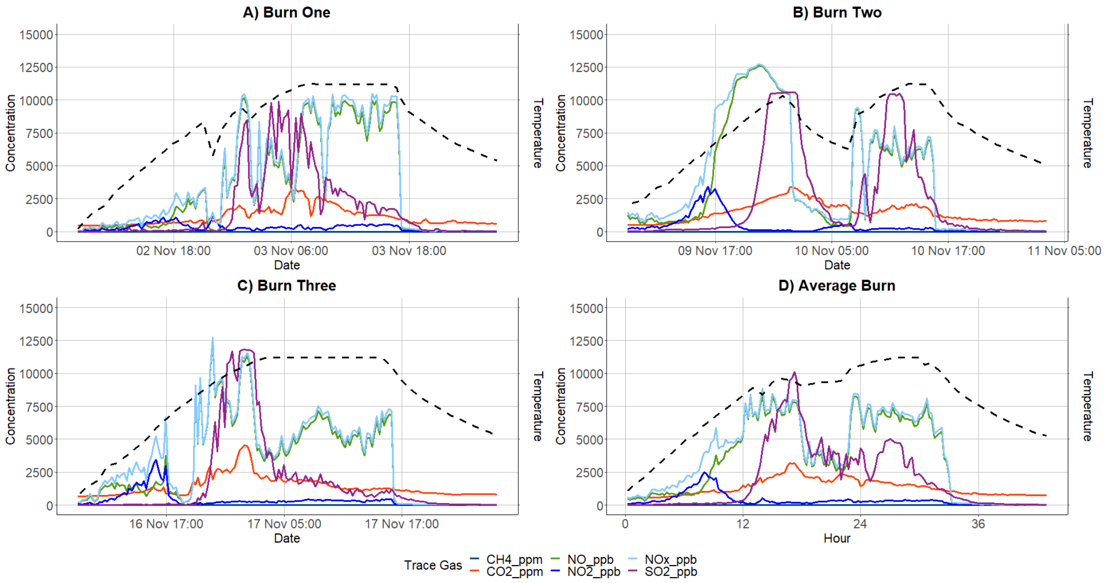


Figure 24: The emissions profiles of Burn One (a), Burn Two (b), Burn Three (c) and the average Hydrogen burn (d). Temperature denoted by dashed black line

7.2.4 Oxides of Nitrogen (NO, NO_2 and NO_x)

The NO, NO_2 and NO_x emission profiles are given in Figure 25 (a to d), with the natural gas profile shown in Figure 29.

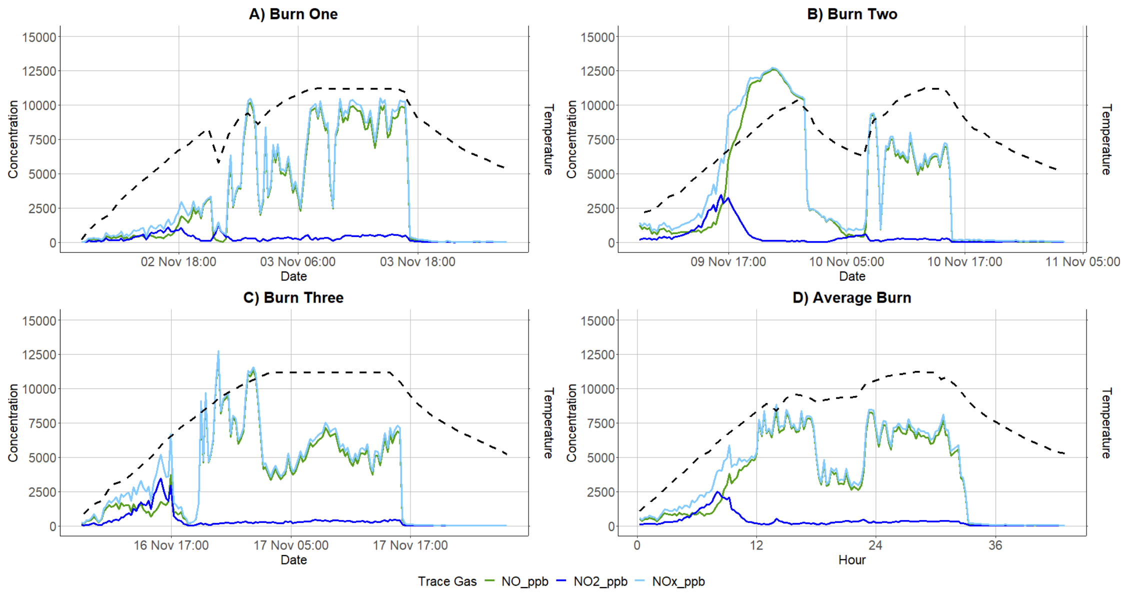


Figure 25: The NO, NO_2 and NO_x emissions profiles of Burn One (a), Burn Two (b), Burn Three (c) and the average Hydrogen burn (d). Temperature denoted by dashed black line

Total NO_x emissions appear to increase in line with an increase in kiln temperature, best illustrated within the Burn Two and Average burn profile. NO_x emissions increase while the temperature is ramping up, and maintain through the "soak" phase of the burn when the kiln is held at the maximum temperature for a number of hours. The onset of the cooling stage aligns with an almost immediate return to background concentration.

NO_2 concentrations steadily increased with total NO_x through the first eight hours of the burn cycle, before reducing back to near background by hour twelve. Conversely, NO continued to rise with total NO_x, with total NO_x being comprised almost entirely of NO after hour twelve. This would suggest that the atmosphere within the kiln starts to become Oxygen deficient around eight hours into the cycle, with this deficiency resulting in a higher proportion of NO compared to NO_2.

The trend seen in NO_2 emissions during the hydrogen trials was replicated through the natural gas trial, with an initial increase in NO_2 and NO followed by a reduction in NO_2 and increase in NO.

Total NO_x concentrations were notably higher during the hydrogen burns than the equivalent natural gas burn. Total NO_x emissions peaked at ~10,000 ppb during Burn One and at ~12,500 ppb in both Burn Two and Burn Three, compared to a peak of 6,350 ppb during the natural gas cycle.

7.2.5 Sulphur Dioxide (SO_2)

The SO_2 emission profiles are given in Figure 26 (a to d), with the natural gas profile shown in Figure 29.

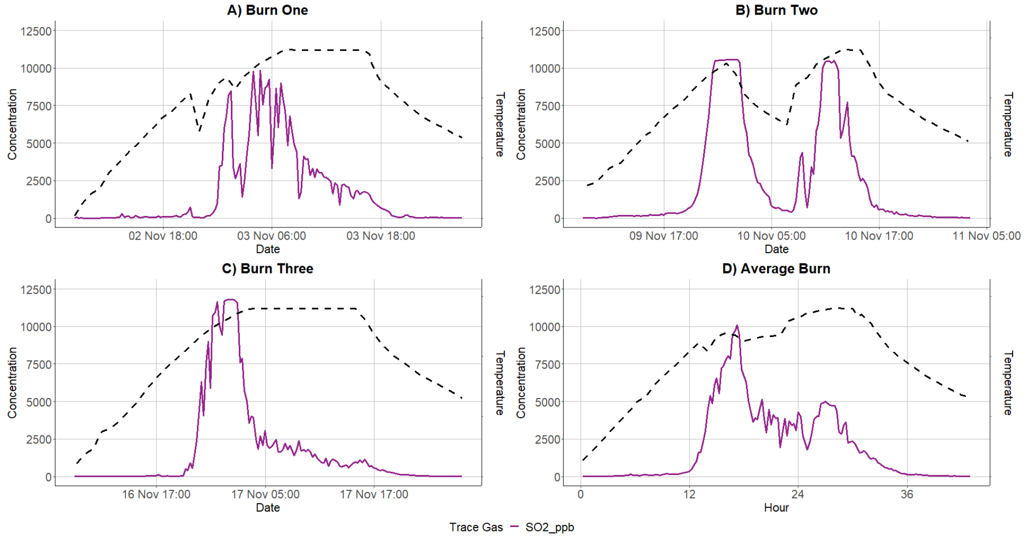


Figure 26: The SO_2 emissions profiles of Burn One (a), Burn Two (b), Burn Three (c) and the average Hydrogen burn (d). Temperature denoted by dashed black line

SO_2 emissions increased in line with the temperature of the kiln; they increased gradually throughout the initial 12 hours of the burn cycle, before seeing an exponential rise which aligns with the kiln reaching its target temperature. During Burn Two, SO_2 concentrations rapidly declined where the heating programmed was interrupted during the early hours of November 10th.

The concentration profiles of Burns One and Three suggest that the Sulphur content within the bricks is rapidly reduced, as SO_2 emissions gradually begin to reduce following a short period at peak temperature. This is best exemplified by Burn Three, in which the kiln temperature curve was the most consistent, with SO_2 emissions peaking at ~12,000 ppb for a short period before seeing a rapid reduction to ~2,500 ppb. The emissions then gradually return to background over the remainder of the heating cycle.

SO_2 emissions during the natural gas trial were comparable to those of the hydrogen trials, suggesting SO_2 emissions are dictated by the kiln temperature and Sulphur content of the bricks regardless of the fuel used.

7.2.6 Carbon Dioxide and Methane (CO_2 and CH_4)

The CO_2 and CH_4 emission profiles are given in Figure 27 (a to d), with the natural gas profile shown in Figure 29.

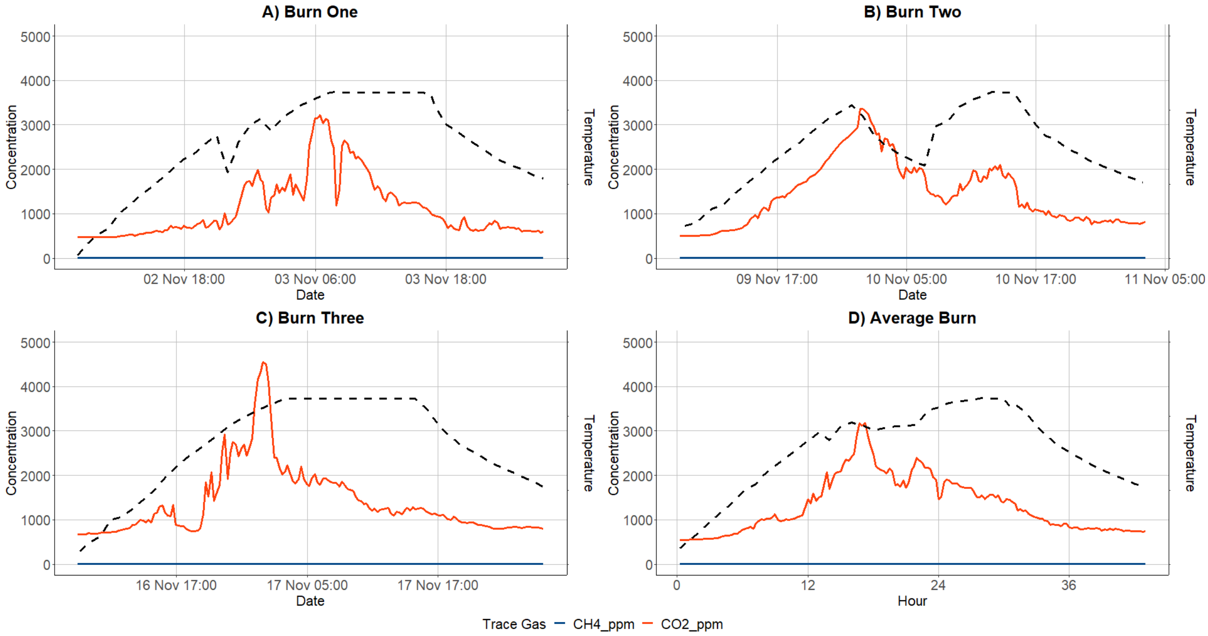


Figure 27: The CO_2 and CH_4 emissions profiles of Burn One (a), Burn Two (b), Burn Three (c) and the average Hydrogen burn (d). Temperature denoted by dashed black line

CH_4 concentration remained at background levels through all three burns, suggesting that no, or very little, CH_4 was produced when utilising hydrogen to fire bricks. CO_2 emissions increase gradually with kiln temperature, which suggests that, like SO_2, CO_2 emissions were the result of the spontaneous combustion of a traditional ingredient within the bricks as overall temperature increased within the kiln. The emission profile of Burn Two again supports this suggestion, with CO_2 emissions peaking in the early hours of November 10^{th}, declining with temperature throughout the morning and then seeing an increase once the heating cycle was resumed.

Given that the bricks contain a traditional combustible ingredient which is burnt during the firing cycle, it is expected that a cycle using hydrogen as fuel would still produce some amount of CO_2, although total GHG emissions are expected to be markedly lower given the combustion of natural gas would be a further source of CO_2 through a typical combustion cycle. During the natural gas burn, CO_2 emissions peaked at 13,696 ppm compared to 3,175 ppm during the average hydrogen cycle, suggesting that CO_2 emissions are reduced significantly where hydrogen is used as an alternative to natural gas.

Small but notable concentrations of CH_4 were recorded during the natural gas trial peaking at 21 ppm, with such emissions not recorded at any point through the hydrogen trials. This would suggest there to be some degree of incomplete combustion within the burner itself. Such emissions are notable as CH_4 (fossil origin) is considered to have a global warming potential (GWP) of 29.8 over a 100-year time period (IPCC, Sixth Assessment Report, 2021).

7.2.7 Water Vapour (H_2O)

The H_2O emission profiles are given in Figure 28 (a to d), with the natural gas profile shown in Figure 29.

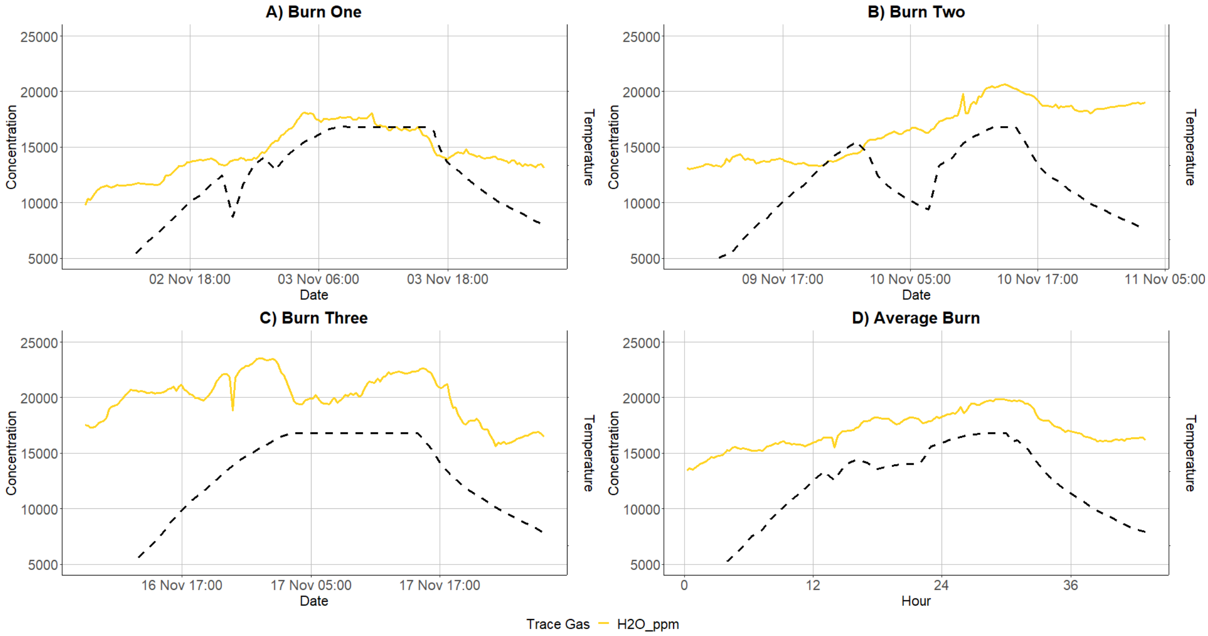


Figure 28: The H_2O emissions profiles of Burn One (a), Burn Two (b), Burn Three (c) and the average Hydrogen burn (d). Temperature denoted by dashed black line

The overall trend in H_2O concentration is somewhat difficult to assess fully given the outdoor nature of the project. However, per the Average Burn, H_2O concentrations would appear to increase throughout the initial ~30 hours of the burn cycle, before reducing slightly through the end of the cycle. This trend aligns well with the temperature of the kiln. However, such a trend is only seen well within the profile of Burn One, with both Burn Two and Burn Three showing some aspects of this trend. H_2O concentration need not follow this trend during the natural gas burn, which may suggest that the combustion of hydrogen was responsible for this trend. To assess this trend further, meteorological data could be assessed along with H_2O concentration.

7.2.8 Natural Gas Trial

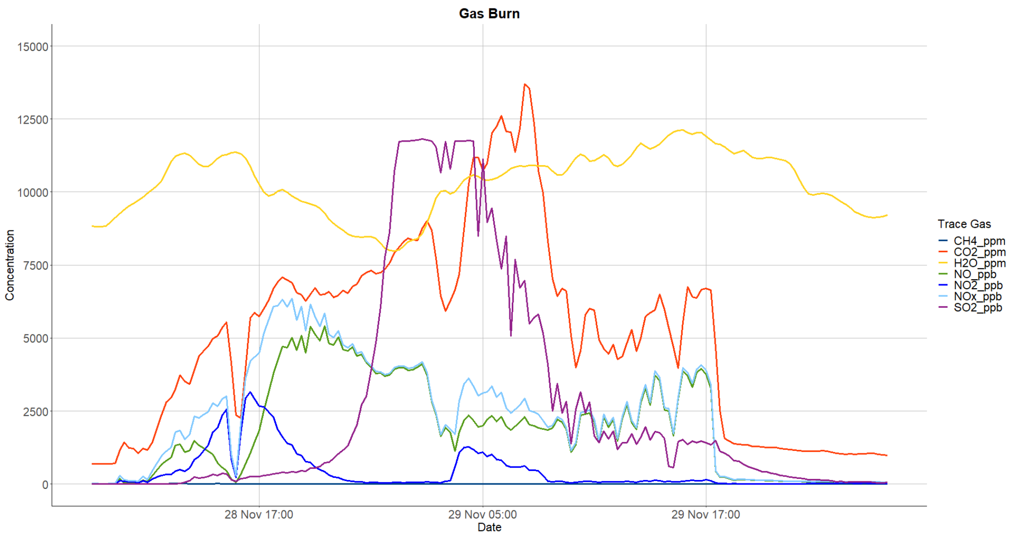


Figure 29: The emissions profiles of the natural gas trial (temperature not shown)

8. WP3: Develop & Conduct Lab Testing of 1050 kW H_2Ready Burners

The final work package was to develop and conduct lab testing of larger hydrogen ready burners, the same size as those currently used in the drying chambers at Freshfield Lane. If the Project continued to Demonstration Phase (Phase 2), this would demonstrate - at industrial scale - the effectiveness of firing hydrogen in the drying process.

For this project Limpsfield selected a standard burner from their range to cover the natural gas firing to meet the site requirements for the dryers at Freshfield Lane.

Limpsfield utilizes the spider head design for their burners, a proven technology for firing hydrogen as well as other gases. Based on the required heat output, the burner is scaled accordingly to achieve the correct injection velocities for flame stability and complete mixing with the oxidizer. The spider head design injects hydrogen in front of the diffuser plate with flame retention maintained by the air pressure differential over the diffuser plate.

Limpsfield then changed the gas head manifold to convert the burner to fire hydrogen. The hydrogen gas head are designed and developed on field fired and proven applications ranging from 60kW up to 8.8MW. The same design principles are followed and scaled to suit the required burner output needed for a specific application. In house testing and validation was then carried out.

Figure 30: Test setup for hydrogen firing (Limpsfield Lab)

8.1 Limpsfield Lab Test Results

	MM				TESTO						EGA						TESTO	EGA	PRESSURES					
					EMISSIONS												TEMPERATURES							
	CH1	CH2	CH3	CH4	O2	CO2	CO	NO	NO2	NOX	O2	CO2	CO	NO	NO2	NOX***	T1	T2	P1	P2	P3	P4	P5	P6
	deg	deg	deg	Out (mA)	%Vol	%Vol	ppm	ppm	ppm	ppm	%Vol	%Vol	ppm	ppm	ppm	ppm	°C	°C	mbar	mbar	mbar	mbar	mbar	mbar
Open	90.0	90.0	-																					
High	40.0	60.0	-	20.0	2.7	10.3	7	59	8.1	67.1	2.8	10.9	7	61	-	64	56.2	54.0	-	17.9	15.1	4.9	-0.1	15.0
	30.9	45.7	-	17.5	2.6	10.4	7	60	8.3	68.3	2.6	11	8	63	-	65	61.0	60.0	-	15.2	13.0	4.0	-0.1	13.3
	25.8	38.2	-	14.7	2.8	10.3	5	60	8.3	68.3	2.8	10.9	6	63	-	66	62.7	62.0	-	12.4	10.6	3.2	-0.1	11.3
	20.4	23.1	-	14.4	3.1	10.2	4	58	8.3	66.3	3.1	10.8	5	60	-	64	62.8	62.0	-	8.3	7.2	2.0	-0.1	11.2
	15.0	16.5	-	11.1	3.2	10.0	4	57	7.0	64.0	3.2	10.7	3	60	-	65	60.6	60.0	-	3.8	3.4	0.9	-0.1	9.3
	11.9	12.7	-	9.1	3.0	10.2	5	59	6.0	65.0	3	10.8	4	63	-	67	57.4	56.0	-	2.1	1.9	0.4	-0.2	8.2
Low	9.5	10.7	-	7.3	3.2	10.1	5	59	6.2	65.2	3.2	10.7	5	63	-	68	54.9	54.0	-	1.5	1.4	0.3	-0.1	7.2
Purge	0.0	90.0	-																	14.0	15.3	3.9	-0.1	15.0
Closed	0.0	0.0	-																					

Comments: *VSD Reading
** Tachometer Reading
***At 3% O2 (EGA)
Ambeint temp. 18C

Date:

T1	Flue Testo	P1	Gas Pressure Sensor
T2	Flue EGA	P2	Gas Head Presure
		P3	Windbox Pressure
		P4	Furnace Pressure
		P5	Stack Pressure
		P6	Air Inlet Pressure (Sensor)

Table 5: Burner Emission Testing - Firing Natural Gas

Burner Model:	LC9 (Derated)																		
Fuel type:	H_2					Fuel CV:		HHV 141.788 MJ/kg											
						EGA			Testo										
	CH1	CH2	CH3	CH5		O2	NOX	Temp.	O2	NOX	Temp.	Bottle Reg	Gas Train Inlet	Step Down	Gas Sensor	ΔP	Gas Head	Windbox	Furnace
	Deg	Deg	Deg	mA out	mA in	%Vol	ppm	°C	%Vol	ppm	°C	Bar		mbar					
Open	90.0	90.0	90.0	20.0	20.0														
6% O_2 Test																			
High	34.5	26.3	0.0	16.9	-	6.0	126	47	6.0	112	49	4.8	-	300.0		14.0	195	8.3	4.0
3% O_2 Test																			
High	34.5	26.3	0.0	11.1	-	2.9	125	38	2.9	132	38	4.8	4.0	300.0		14.0	195	5.9	3.1
Low	10.0	12.3	0.0	11.8	-	3.0	163	27	2.9	167	29	4.8	4.4	300.0		2.5	59	1.3	0.6
Purge	0.0	90.0	0.0	20.0	-													15.0	
Close	0.0	0.0	0.0	4.0	4.0														

Table 6: Burner Emission Testing - Firing Hydrogen

The lab testing included testing for any heat or visible damage to the burner components while firing hydrogen. Small adjustments to the location of the orifices of the gas head were carried out to enable a better heat distribution.

The initial bench tests firing hydrogen achieved NO_x levels of 125-163ppm at 3% O_2 (Table 9, above).

However, NO_x levels of 39ppm were then achieved by reducing oxygen levels to 2.5% and carrying out flue gas recirculation (FGR). This is lower than the Medium Combustion Plant Directive (MCPD), which has NO_x limits for new plants[2] of 100mg/m^3 for natural gas (approx. 50 ppm). This low NO_x level was stable, and therefore could be replicable.

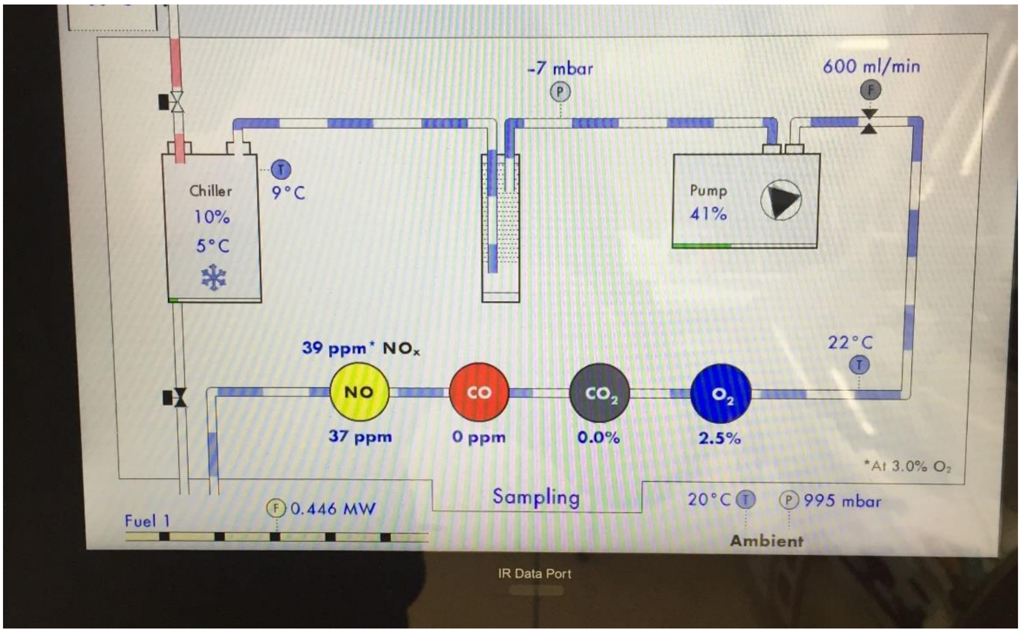


Figure 31: Low NO_x achieved during bench tests

Figure 32: Limpsfield Hydrogen Ready Burner

[2] Medium Combustion Plant Directive (MCDP): New plant NO_x limits are 100 mg/m^3 for natural gas for all plants individually 1-50 MWth net rated thermal input. Under the MCPD definition, changing the fuels being combusted (i.e. switching from natural gas to hydrogen) would qualify as a '*new*' plant.

9. Results

9.1 Technology Readiness Level (TRL)

At the project onset, the Technology Readiness Level was at TRL 5 (pilot stage).

By the end of this Feasibility Project, the project demonstrated Technology Readiness Levels TRL 6 (technology demonstrated in relevant environment) to TRL 7 (system prototype demonstration in operational environment) through the on-site demonstration at Michelmersh's Freshfield Lane site.

9.2 Technical Performance

This Feasibility Project trialled the deep decarbonisation of the brick manufacturing process, assessing the feasibility of converting an existing gas kiln to use hydrogen instead of natural gas to fire the bricks.

Hydrogen exhibits different properties to natural gas when fired. There were no issues with achieving high temperatures when firing hydrogen. At low temperatures (below 175°C), the kiln temperature tended to overshoot the set point.

Overall, the 3 hydrogen burns showed that it is technically possible to fire bricks using hydrogen – indeed, these bricks were potentially the first ever clay bricks fired with 100% green hydrogen in an operational brick kiln in the world.

The second hydrogen burn, where the temperature accidentally dropped from above 1000°C down to 625°C over a period of 7 hours was able to be rectified; hydrogen managed to bring the temperature back up far quicker than natural gas would have done. This burn would likely have not been salvageable with natural gas.

However, firing bricks to achieve the structural and aesthetic requirements was more challenging. The natural gas trials with the Limpsfield hydrogen-ready burner showed that firing bricks with natural gas is more complex than originally realised, and that swapping burners is not necessarily a simple like-for-like replacement. Maximum firing temperature, length of time soaking at top temperature, and % air supplied to the kiln are all key parameters, as well as the flame speed and burner output. Repeated natural gas trials were required to vary each parameter to achieve a brick which met the technical requirements of Michelmersh's Freshfield Lane *First Quality Multi* bricks.

Although the three hydrogen trials were successful and produced bricks that met the general technical requirements (dimensions, compressive strength, water absorption) of clay bricks, additional hydrogen trials would be required. This would enable the firing process to be fine-tuned to achieve the specific technical requirements of the bricks being fired, especially with regard to eliminating bloating and producing bricks within the required dimensional tolerances.

9.3 Carbon Emission Savings

Assuming that 100% of the fuel was fired during all burns (and there were therefore no fugitive methane emissions), the carbon emissions from the hydrogen burns are outlined in the table below (assuming an average 3gCO_2e/MJ for production of the green hydrogen, and 5gCO_2e/MJ for downstream distribution emissions, resulting in overall lifecycle GHG emissions of green hydrogen to be 8gCO_2e/MJ). All three hydrogen burns achieved reductions in carbon emissions of 80 - 84%.

Hydrogen Burns	**MJ**	**kgCO_2e** (if 8gCO_2e/MJ)	**Reduction in CO_2e Emissions Compared to Original NG Burner**
H_2 Trial 1	7651.4	61	81%
H_2 Trial 2	6779.3	54	84%
H_2 Trial 3	8098.5	65	80%

Table 7: Carbon Emissions from Hydrogen Burns, Assuming Carbon Conversion Factor of 8gCO_2e/MJ)

Longer term, if Michelmersh were able to produce hydrogen onsite, using onsite renewables, this would result in lower overall lifecycle GHG emissions of green hydrogen of under 5gCO_2e/MJ, and a reduction in the gas emissions of 88 - 90%.

Hydrogen Burns	**MJ**	**kgCO_2e** (if 5gCO_2e/MJ)	**Reduction in CO_2e Emissions Compared to Original NG Burner**
H_2 Trial 1	7651.4	38	88%
H_2 Trial 2	6779.3	34	90%
H_2 Trial 3	8098.5	40	88%

Table 8: Carbon Emissions from Hydrogen Burns, Assuming Carbon Conversion Factor of 5gCO_2e/MJ

This data was verified by the Air Quality Monitoring results, where CO_2 emissions were directly monitored during all hydrogen trials and during one natural gas burn. The monitoring picked up CO_2 emissions during all firings, including the hydrogen trials. This was due to the traditional ingredient within the bricks which was burnt during the firing process.

During the natural gas burn, CO_2 emissions peaked at 13,696 ppm compared to 3,175 ppm during the average hydrogen cycle, suggesting that CO_2 emissions are reduced by up to 75% where hydrogen is used as an alternative to natural gas.

Small but notable concentrations of CH_4 were recorded during the natural gas trial peaking at 21 ppm, with such emissions not recorded at any point through the hydrogen trials. This would suggest there to be some degree of incomplete combustion within the burner itself. Such emissions are notable as natural gas (fossil origin) is considered to have a global warming potential (GWP) of 29.8 over a 100-year time period[3].

The latest estimate for the GWP for hydrogen is 11 ± 5 over a 100-year time horizon[4], but this is still below the GWP of natural gas. If Michelmersh were to convert to hydrogen at scale, work would be needed to reduce all fugitive emissions (including during actual combustion) to as close to zero as possible.

[3] IPCC, Sixth Assessment Report, 2021

[4] Frazer-Nash Consultancy, Fugitive Hydrogen Emissions in a Future Hydrogen Economy, 2022

9.4 Other Atmospheric Emissions

As previously noted, although firing hydrogen achieved a significant reduction in carbon emissions, total NO_x concentrations were notably higher during the hydrogen burns than the equivalent natural gas burn. Total NO_x emissions peaked at ~10,000 ppb during Burn One and at ~12,500 ppb in both Burn Two and Burn Three, compared to a peak of 6,350 ppb during the natural gas cycle.

Whilst the NO_x emissions increased during the hydrogen burns, these emissions were still lower than the Medium Combustion Plant Directive (MCPD), which has NO_x limits for new plants of 100mg/m^3 for natural gas (approx. 50 ppm, or 50,000 ppb).

However, it should be noted that the sampling equipment was positioned just beyond the kiln stack and caused the sample to be somewhat diluted. The relative values recorded are all absolutely robust (e.g. NO_x emissions consistently over 50% higher during hydrogen burns than during natural gas burns), but any sampling for the MCPD would need to be from within the kiln stack to avoid dilution of the sample.

Limpsfield also managed to significantly reduce NO_x levels when firing hydrogen in the lab by carrying out flue gas recirculation (FGR). The initial bench tests firing hydrogen achieved NO_x levels of 125-163ppm at 3% O_2, but NO_x levels of 39ppm were then achieved by reducing oxygen levels to 2.5% and carrying out flue gas recirculation. If Michelmersh decide to switch to hydrogen in their brick production, it could be possible to reduce NO_x levels further by installing FGR equipment in their kilns.

SO_2 emissions during the natural gas trial were comparable to those of the hydrogen trials, suggesting SO_2 emissions are dictated by the kiln temperature and Sulphur content of the bricks regardless of the fuel used.

9.5 Contribution to Net Zero

If hydrogen were implemented into the wide variety of different manufacturing sites, equipment and processes across the Michelmersh Group it would reduce gas emissions by 90%, with further replication across the brick and wider ceramic industry leading to significant savings on a national level.

10 Further Discussion

10.1 Health and Safety / Regulatory Issues

The following health & safety and regulatory challenges were observed during the project:
• Policies, guidance and standards had not been established locally or on a national scale.
• There was a lack of training resources and experience in operating procedures for this specific application/use.
• Misconception / preconceived reputation of hydrogen.

From the work undertaken during the project, the potential risks and implications led to the following conclusions:
• The use of hydrogen on-site in any quantity greatly increases the risk profile of the premises, regardless of the controls in place. As such full competency and confidence in safety operations must be ensured.
• Appropriate involvement of fire services will always be required - emergency response procedures are still relevant for hydrogen. It would be useful to see the fire service involved in a future project as a partner or at least involved in part of any HAZOP discussions.
• It is important to note that working with hydrogen in any capacity is outside of Michelmersh's usual scope of operation; as such the expertise in working with hydrogen did not sit within the business. This meant that Michelmersh became heavily reliant on the information being provided and relayed by third parties.
• All partners worked together to deliver the scope of the project while also meeting Michelmersh's requirement to deliver health and safety as a priority. The partners were all open and honest in raising safety issues to ensure all risks and hazard were fully addressed and worked in a collaborative manner to ensure controls were suitable and sufficient.

The most significant regulatory issue encountered during the Feasibility Project was the lack of clear guidance from the relevant agencies. It took significant effort (involving a number of parties) to obtain the following feedback from the Environment Agency:

> "Without prejudice, we do not believe that there are any permitting requirements for a trial on brickmaking from the Environment Agency's point of view."

If the trial is successful, and hydrogen fuelled systems are used at site, significant wider permitting requirements will need to be met. Very large volumes of hydrogen would be required onsite.

The controlled quantity of hydrogen for the Planning (Hazardous Substances) Regulations 2015 is 2 tonnes. Hydrogen is a named dangerous substance under COMAH regulations; the threshold quantities are 5 tonnes (lower tier) and 50 tonnes (upper tier). Full COMAH, DSEAR and FERA assessments would therefore also need to be undertaken for any planned system.

10.2 Route to Market Assessment

2022 saw the return of double-digit inflation - which is predicted to continue into 2023 - with volatile natural gas prices causing a significant increase in costs to brick manufacturers across the UK. Supply chain issues are being seen across many sectors of the economy and many products and items are proving difficult to obtain without extended lead times. This was also seen within our project on the supply of integral parts to the hydrogen Pressure Reducing Skid.

Without further economic modelling to assess the financial viability and the supply of green hydrogen for trials, let alone industrial use, it would be difficult to access fully considered commercialisation routes or time frames. A predicated reduction in hydrogen costs means that it could be financially beneficial to switch to hydrogen in the early 2030s, or financially optimal to switch to hydrogen in the early 2040s.

The sector's energy consumption is split at approximately 85% gas and 15% electricity. Hydrogen is therefore seen as a key decarbonisation route for most parts of the ceramic sector.

Factors which would play a role in tipping the balance towards earlier fuel switch adoption are:

- Government Policy: e.g. subsidies on fuel costs, increased carbon taxes
- Supply Chain Development: e.g. Advances in hydrogen generation, increase in market competitiveness
- Industry Development: e.g. hydrogen firing increases fuel efficiency, reduces maintenance requirements

Another common theme experienced throughout the project is the lack of industrial Health and Safety information in relation to hydrogen use on an operational site. It was obviously of paramount importance for all partners, but especially for lead partner Michelmersh, for these trials to take place safely. Further work on improving standards, documentation and regulation would help drive more support and ambition to trail hydrogen further.

There is a critical path of testing required for the drying process of brick manufacturing and other types of kiln firing to understand if hydrogen is the most efficient and lowest carbon route for manufacturers to switch to. Therefore, to predict the possible rollout potential would be too soon, as the critical path will tell if hydrogen can firstly be used throughout the entire manufacturing process, and secondly if it is the most sustainable route.

Conclusions consist of the costs of decarbonisation using hydrogen being too high and cannot easily be met by the company without support in the form of subsidies or grants. If the site were to come into ETS, there could appear to be an economic driver for switching from natural gas to hydrogen, but this would only be to reduce the extra cost of carbon imposed by the ETS scheme. The extra costs and burden of ETS could mean the company would be unable to continue to operate. In the scenario where the site comes under the ETS, the greatest benefits would be found in switching the kilns with the highest energy consumption rate. Other factors would need to be applied to balance out the costs of switching to hydrogen firing to make it attractive to manufacturers and the hydrogen generation economy needs to be much more developed to cope with the demand if manufacturers do prove that hydrogen is the best possible route from an economic, commercial and carbon perspective.

10.3 Lifetime Costs of Carbon

The total costs of the project were £292.6k. The current high price of green hydrogen (approx. £50/kg) means that fuel switching to hydrogen is not yet economically feasible, and the lifetime costs of carbon are prohibitively high.

However, the price of green hydrogen is expected to drop significantly over this decade. When considering fuel costs alone, the hydrogen price would need to reduce to approx. £6/kg to be comparable to that of natural gas. However, as mentioned previously, if the site were to come into ETS, there could be an economic driver for switching from natural gas to hydrogen. This would also greatly reduce the lifetime costs of carbon.

10.4 Next Steps

When planning this Feasibility project, the project partners were also considering the next phase if the feasibility were successful. In the Phase 2 (Demonstration) project, the partners would be looking to demonstrate the effectiveness of hydrogen burners at industrial scale. The plan was to trial firing hydrogen using the larger hydrogen burners in the drying process.

However, whilst this Feasibility project was a success, Michelmersh has become increasingly aware of the cost and complexity of working with hydrogen at scale, with still many unknowns regarding its other types of manufacturing methods and facilities. Only through a thorough path of critical testing would the manufacturer feel confident to alter all infrastructure at a cost of millions per site; especially if an electrolyser to produce hydrogen on its land was the most commercially sensible option. Therefore, it is also exploring alternative improvements in competing technologies, especially in lower temperature applications, whilst continuing its research with hydrogen.

There are increasing zero carbon alternatives to natural gas when heating to the lower temperatures required in the dryers. As a result, Michelmersh are looking to investigate all appropriate decarbonisation options including electric burners and high-temperature heat pumps, before looking to invest significant amount of money in implementing a given method for each of its sites.

Limpsfield Combustion are focusing on continuing to develop their range of hydrogen ready burners, and their expertise in this area. They have recently supplied 2.5MW hydrogen burners to the BEIS green distilleries study in Scotland conducted by Locogen. They are also increasing supply of hydrogen burners to international customers, and have noted a marked increase in interest in firing hydrogen over the last year. This feasibility project helped validate Limpsfield's work developing hydrogen burners, showing that their burners are both scalable and can achieve extremely low NO_x levels, and has also helped provide them with wider contacts across the burgeoning UK hydrogen industry.

10.5 Social Value Delivered Through the Project

There are over 150 ceramic manufacturing sites across the UK, with the ceramics sector employing over 17,500 people directly. Therefore, low carbon hydrogen has a significant role to play in the decarbonisation of ceramics as a whole in the UK.

Since the announcement of this project, Michelmersh has experienced increased demand for less embodied carbon clay brick products from housebuilders, contractors and architects within the construction sector. Early adopters of hydrogen technologies across UK clay brick manufacturers could lead to significant growth across the sector due to the competitive advantage this provides over the high number of imported overseas products produced with fossil fuels.

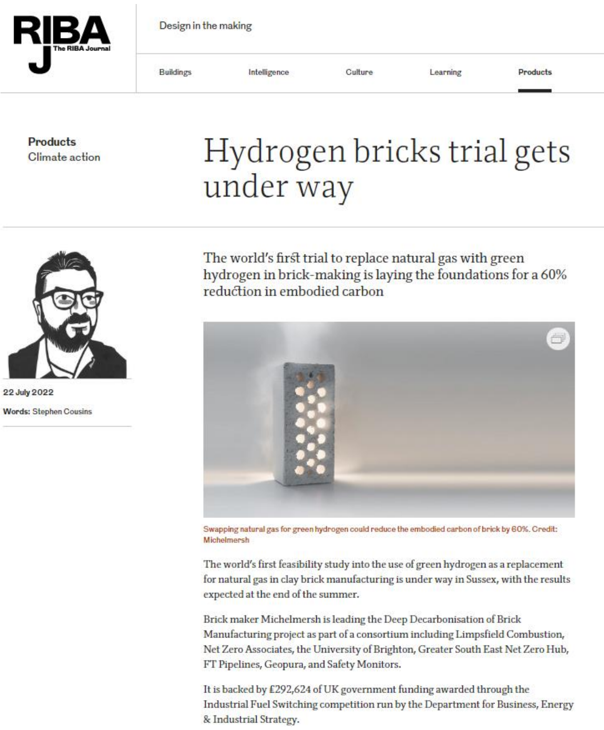
This *Deep Decarbonisation of Brick Manufacturing* project has engaged with a wealth of expert partners, specialist subcontractors, education faculties and suppliers. HyBrick as Michelmersh branded its research in general, has been presented by the Brick Specialist nationally at Net Zero conferences, hydrogen-related events, ceramic industry events, on national publications, at the World Architecture Festival and many others. Television companies have shown an interest in exploring the potential that can be sought, for products that are integral to the makeup of the UK's built environment and that promote sustainability through the longevity and durability characteristics that the clay brick inspires.

With the project demonstrating the potential opportunity to use 100% hydrogen in clay brick manufacturing, it is delivering social value to support the manufacture of low-carbon ceramic products in the UK. Thus, the project has contributed to the journey of enabling hydrogen as a decarbonisation option.

10.6 Dissemination and Industry Engagement

There has been extensive interest in this project, from within the UK ceramics industry, across the wider construction industry, and from further afield. Dissemination has included a video for the Supply Chain Sustainability School, presentations and panels, and dozens of articles.

This culminated in receiving the award of 'Decarbonisation Trailblazer' at the inaugural *Delivering Net Zero for British Ceramics* conference, hosted by the British Ceramic Confederation.



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Hydrogen bricks trial gets under way

22 July 2022
Words: Stephen Cousins

The world's first trial to replace natural gas with green hydrogen in brick-making is laying the foundations for a 60% reduction in embodied carbon

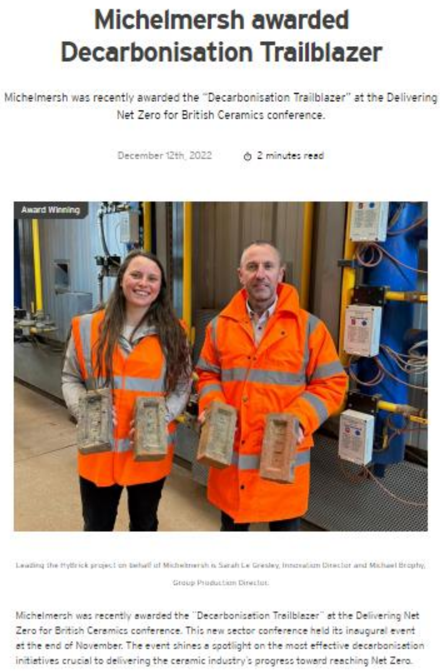
Swapping natural gas for green hydrogen could reduce the embodied carbon of brick by 60%. Credit: Michelmersh

The world's first feasibility study into the use of green hydrogen as a replacement for natural gas in clay brick manufacturing is under way in Sussex, with the results expected at the end of the summer.

Brick maker Michelmersh is leading the Deep Decarbonisation of Brick Manufacturing project as part of a consortium including Limpsfield Combustion, Net Zero Associates, the University of Brighton, Greater South East Net Zero Hub, FT Pipelines, Geopura, and Safety Monitors.

It is backed by £292,624 of UK government funding awarded through the Industrial Fuel Switching competition run by the Department for Business, Energy & Industrial Strategy.

Figure 33: Article in The RIBA Journal



Michelmersh awarded Decarbonisation Trailblazer

Michelmersh was recently awarded the "Decarbonisation Trailblazer" at the Delivering Net Zero for British Ceramics conference.

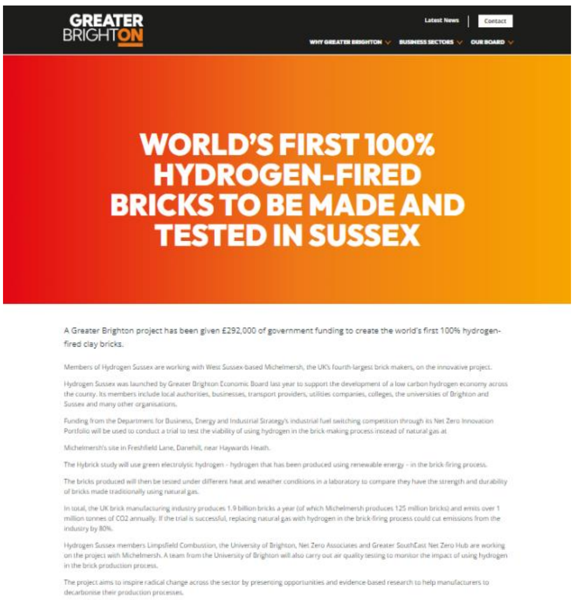
December 12th, 2022 · 2 minutes read

Award Winning

Leading the HyBrick project on behalf of Michelmersh is Sarah Le Gresley, Innovation Director and Michael Brophy, Group Production Director.

Michelmersh was recently awarded the "Decarbonisation Trailblazer" at the Delivering Net Zero for British Ceramics conference. This new sector conference held its inaugural event at the end of November. The event shines a spotlight on the most effective decarbonisation initiatives crucial to delivering the ceramic industry's progress toward reaching Net Zero.

Figure 34: Michelmersh Awarded Decarbonisation Trailblazer



GREATER BRIGHTON

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WORLD'S FIRST 100% HYDROGEN-FIRED BRICKS TO BE MADE AND TESTED IN SUSSEX

A Greater Brighton project has been given £292,000 of government funding to create the world's first 100% hydrogen-fired clay bricks.

Members of Hydrogen Sussex are working with West Sussex-based Michelmersh, the UK's fourth-largest brick makers, on the innovative project.

Hydrogen Sussex was launched by Greater Brighton Economic Board last year to support the development of a low carbon hydrogen economy across the county. Its members include local authorities, businesses, transport providers, utilities companies, colleges, the universities of Brighton and Sussex and many other organisations.

Funding from the Department for Business, Energy and Industrial Strategy's industrial fuel switching competition through its Net Zero Innovation Portfolio will be used to conduct a trial to test the viability of using hydrogen in the brick-making process instead of natural gas at

Michelmersh's site in Freshfield Lane, Danehill, near Haywards Heath.

The Hybrick study will use green electrolytic hydrogen - hydrogen that has been produced using renewable energy - in the brick-firing process.

The bricks produced will then be tested under different heat and weather conditions in a laboratory to compare they have the strength and durability of bricks made traditionally using natural gas.

In total, the UK brick manufacturing industry produces 1.9 billion bricks a year (of which Michelmersh produces 125 million bricks) and emits over 1 million tonnes of CO2 annually. If the trial is successful, replacing natural gas with hydrogen in the brick-firing process could cut emissions from the industry by 80%.

Hydrogen Sussex members Limpsfield Combustion, the University of Brighton, Net Zero Associates and Greater SouthEast Net Zero Hub are working on the project with Michelmersh. A team from the University of Brighton will also carry out air quality testing to monitor the impact of using hydrogen in the brick production process.

The project aims to inspire radical change across the sector by presenting opportunities and evidence-based research to help manufacturers to decarbonise their production processes.

Figure 35: Greater Brighton website

News 7 June 2022 by Alex Brinded

Bricks to be made using only hydrogen energy

The HyBrick project will use green hydrogen to make clay bricks.

© diesektion / unsplash

Brickmaker Michelmersh, UK, will lead a consortium to make a 100% hydrogen fired brick.

Their winning bid from the Industrial Fuel Switching competition - run by the UK Goverment's Department for Business, Energy & Industrial Strategy - allows the company to conduct a feasibility study into replacing natural gas with hydrogen for brick making.

Phase one will demonstrate the viability of fuel switching with hydrogen used in clay brick production at Michelmersh's Freshfield Lane site using green electrolytic hydrogen.

This project is a part of the £1bln Net Zero Innovation Portfolio to fund low-carbon technologies.

Figure 36: Institute of Materials, Minerals & Mining

11. Conclusions

This Feasibility Project trialled the deep decarbonisation of the brick manufacturing process, assessing the feasibility of converting an existing gas kiln to use hydrogen instead of natural gas to fire the bricks.

The Pre-Feasibility report (WP1) identified the hydrogen standards, infrastructure, safety and other requirements / considerations needed to be met for the successful deployment of hydrogen onsite.

A key stage of WP2 was to install the Limpsfield hydrogen-ready burner in the stand-alone kiln and to fire it using natural gas. The natural gas trials showed that firing bricks with natural gas is more complex than originally realised, and that swapping burners is not necessarily a simple like-for-like replacement. Maximum firing temperature, length of time soaking at top temperature, and % air supplied to the kiln are all key parameters, as well as the flame speed and burner output. Repeated natural gas trials were required to vary each parameter to achieve a brick which met the specific technical requirements.

Three hydrogen burns then took place, which all resulted in completed burns. Hydrogen exhibits different properties to natural gas when fired; it is able to ramp up temperatures more quickly and there were no issues with achieving high temperatures. At low temperatures (below 175°C), the kiln temperature tended to overshoot the set point.

The second hydrogen burn, where the temperature accidentally dropped from above 1000°C down to 625°C over a period of 7 hours was able to be rectified; hydrogen managed to bring the temperature back up far quicker than natural gas would have done. This burn would likely have not been salvageable with natural gas.

Overall, the 3 hydrogen burns showed that it is technically possible to fire bricks using hydrogen – indeed, these bricks were potentially the first ever clay bricks fired with 100% green hydrogen in an operational brick kiln in the world.

However, firing bricks to achieve the structural and aesthetic requirements was more challenging. Although the three hydrogen trials were successful and produced bricks that met the general technical requirements (dimensions, compressive strength, water absorption) of clay bricks, additional hydrogen trials would be required before a whole-scale fuel switch to hydrogen. This would enable the firing process to be fine-tuned to achieve the specific technical requirements of the bricks being fired, especially with regard to eliminating bloating and producing bricks within the required dimensional tolerances.

Assuming that 100% of the fuel was fired during all burns (and there were therefore no fugitive methane emissions), all three hydrogen burns achieved reductions in carbon emissions of 80 - 84%. This data was verified by the Air Quality Monitoring results, where CO_2 emissions were directly monitored during all hydrogen trials and during one natural gas burn. The monitoring picked up CO_2 emissions during all firings, including the hydrogen trials. This was due to the combustible ingredient within the bricks which was burnt during the firing process.

During the natural gas burn, CO_2 emissions peaked at 13,696 ppm compared to 3,175 ppm during the average hydrogen cycle, suggesting that CO_2 emissions were reduced by up to 75% when hydrogen was used as an alternative to natural gas.

Total NO_x concentrations were notably higher during the hydrogen burns than the equivalent natural gas burn. Total NO_x emissions peaked at ~10,000 ppb during Burn One and at ~12,500 ppb in both Burn Two and Burn Three, compared to a peak of 6,350 ppb during the natural gas cycle.

The final work package (WP3) was to develop and conduct lab testing of the 1050 kW hydrogen ready burners. The initial bench tests firing hydrogen achieved NO_x levels of 125-163ppm at 3% O_2. However, NO_x levels of 39ppm were then achieved by reducing oxygen levels to 2.5% and carrying out flue gas recirculation (FGR). This project helped validate Limpsfield's work developing hydrogen burners, showing that their burners are scalable and can achieve extremely low NO_x levels.

If hydrogen were implemented into the wide variety of different manufacturing sites, equipment and processes across the Michelmersh Group it would reduce gas emissions by 90%, with further replication across the brick and wider ceramic industry leading to significant savings on a national level.

When planning this Feasibility project, the project partners were also considering the next phase if the feasibility were successful. In the Phase 2 (Demonstration) project, the partners would be looking to demonstrate the effectiveness of hydrogen burners at industrial scale. The plan was to trial firing hydrogen using the larger hydrogen burners in the drying process.

However, whilst this Feasibility project was a success, Michelmersh has become increasingly aware of the cost and complexity of working with hydrogen at scale, with still many unknowns regarding its other types of manufacturing methods and facilities. There are increasing zero carbon alternatives to natural gas when heating to the lower temperatures required in the dryers. As a result, Michelmersh are looking to investigate all appropriate decarbonisation options including electric burners and high-temperature heat pumps, before looking to invest significant amount of money in implementing a given method for each of its sites.

Limpsfield Combustion are focusing on continuing to develop their range of hydrogen ready burners, and their expertise in this area. This feasibility project helped validate Limpsfield's work developing hydrogen burners, showing that their burners are both scalable and can achieve extremely low NO_x levels, and has also helped provide them with wider contacts across the burgeoning UK hydrogen industry.

Appendix

A1. Supporting Documents

BCGA Code of Practice (CP) 33 The Bulk Storage of Gaseous Hydrogen at Users' Premises (Revision 1: 2012)

BCGA GN-13 DSEAR Risk Assessment (2021)

BDA Designing to brickwork dimensions (2018)

BOC Safety Distances for Bulk Gaseous Hydrogen (2015)

BOC Safety Data Sheet Hydrogen, Compressed (Version: 1.6, 2020)

BS EN 771-1:2011 Specification for masonry units. Clay masonry units (+A1:2015)

BS EN 1127-1:2019. Explosive atmospheres. Explosion prevention and protection

Control of Major Accident Hazards (COMAH) Regulations 2015 UK Statutory Instruments (2015) 483

Doujaiji, B. and Al-Tawfiq, J. A. (2010). Hydrogen sulfide exposure in an adult male. Annals of Saudi Medicine, 30: 76–80.

DSEAR (Dangerous Substances and Explosive Atmosphere Regulations) (2002)

DSEAR Approved Code of Practice and guidance (L138, second edition, 2013)

ENA Britain's Hydrogen Blending Delivery Plan (2022)

Environmental Permitting (England and Wales) (Amendment) Regulations 2018, UK Statutory Instruments (2018) No 110 Part 2, Regulation 16, Schedule 25A

European Council Directive 1999/92/EC Potentially Explosive Atmospheres 'ATEX'

European Council Nonbinding Guide to Good Practice for Implementing the Directive 1999/92/EC 'ATEX' Explosive Atmospheres (2005)

FCH Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) Safety Planning and Management in EU Hydrogen and Fuel Cells Projects – Guidance Document

Frazer-Nash Consultancy Fugitive Hydrogen Emissions in a Future Hydrogen Economy (2022)

IGEM/H/1 Reference Standard for low pressure hydrogen utilisation (2021)

IGEM/SR/25 – Hazardous area classification of Natural Gas Installations (Edition 2, 2010)

IGEM/TD/13 – Pressure regulating installations for natural gas, liquified Petroleum Gas (LPG) and LPG/air (Edition 2, 2011)

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., *et al* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

ISO/TR 15916:2015 Basic Considerations for the Safety of Hydrogen Systems (Edition 2, 2015)

National Academies of Sciences, Engineering, and Medicine, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. Washington, DC (2004)

NHBC Standards 2022 (2022)

Planning (Hazardous Substances) Regulations 2015, UK Statutory Instruments (2015) 627

Progressive Energy HyNet Industrial Fuel Switching Feasibility Study Public Report (January 2020)

A2. Site Plan

N

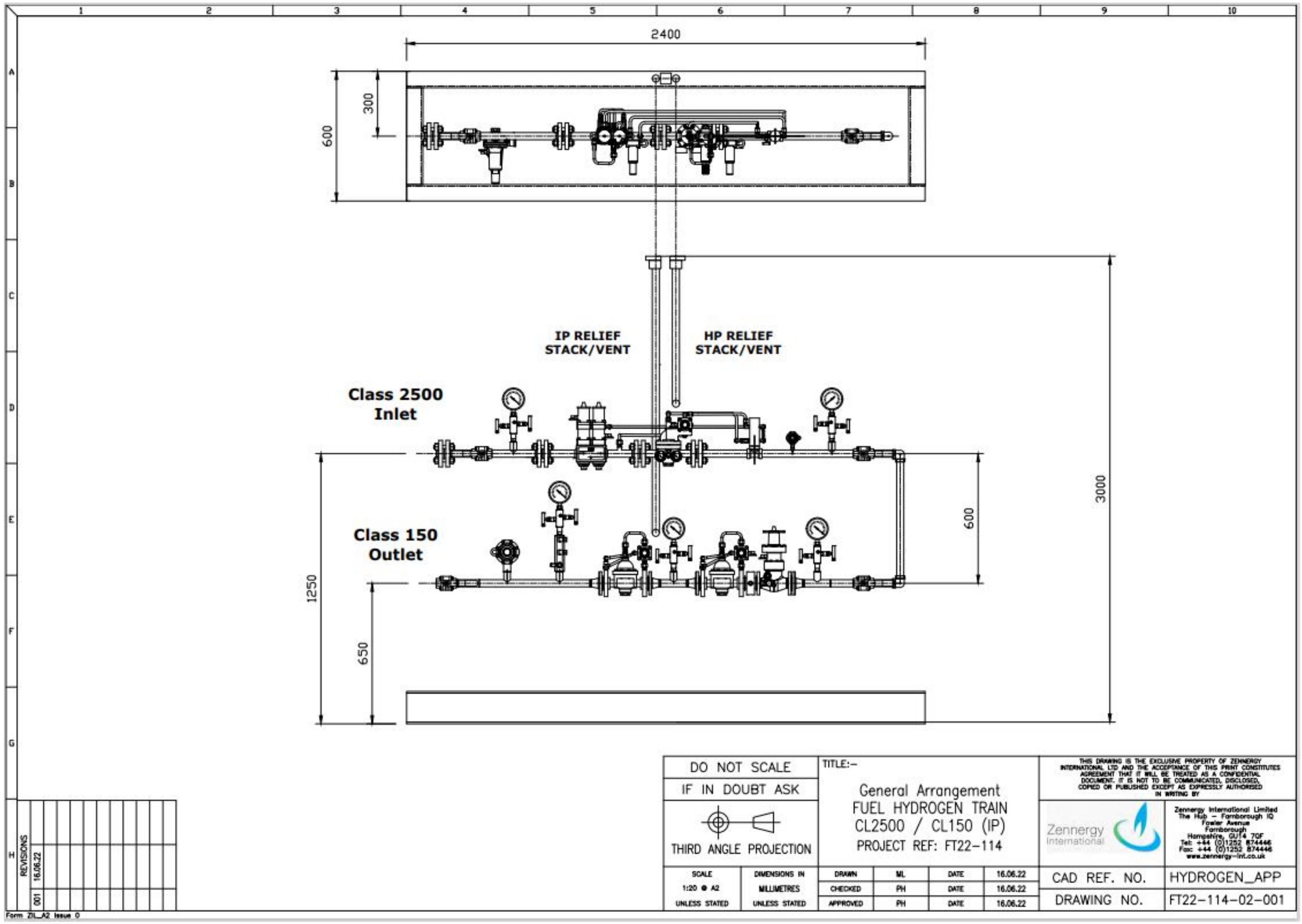
AIMS
AERIAL INSPECTION & MAPPING SURVEYS LTD
3 The Bridge Business Centre, Beresford Way, Chesterfield,
Derbyshire S41 9FG
Tel: 01246 268444
aerialinspectionand mapping surveys.co.uk
johnhalifax@aimsurveys.com

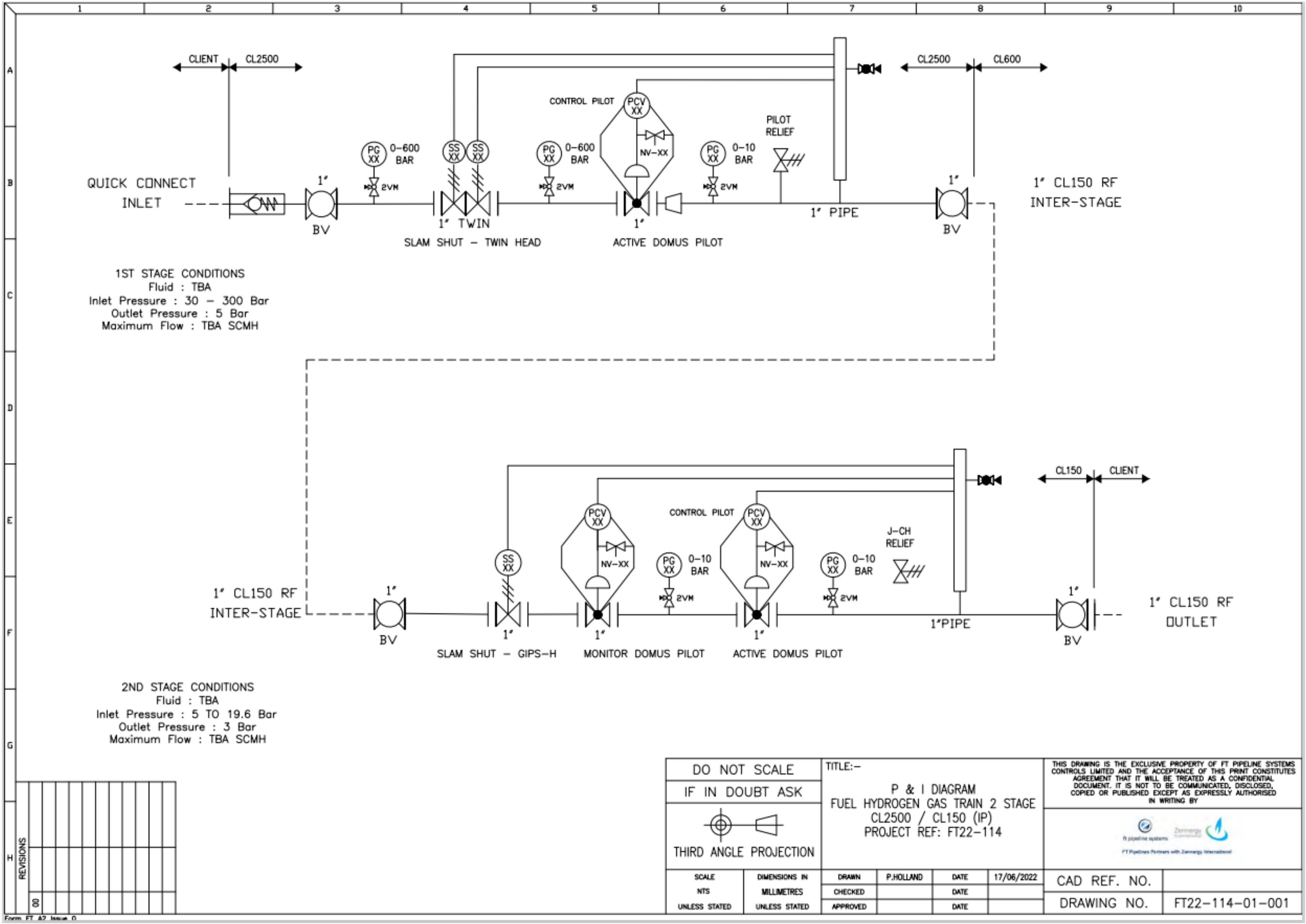
MICHELMERSH
Britain's Brick Specialists

Michelmersh
Brick Holdings PLC
Freshfield Lane
Danehill
Haywards Heath
Sussex
RH17 7HH

Not to Scale

A3. Pressure Reduction Skid Schematic




CLIENT
CL2500
CL2500
CL600
CONTROL PILOT
PCV XX
NV-XX
PILOT RELIEF
PG XX
0-600 BAR
SS XX
0-10 BAR
2VM
QUICK CONNECT INLET
1"
BV
1" TWIN
SLAM SHUT - TWIN HEAD
ACTIVE DOMUS PILOT
1" PIPE
1" CL150 RF INTER-STAGE
1ST STAGE CONDITIONS
Fluid : TBA
Inlet Pressure : 30 - 300 Bar
Outlet Pressure : 5 Bar
Maximum Flow : TBA SCMH
CL150
CLIENT
J-CH RELIEF
1" CL150 RF INTER-STAGE
SLAM SHUT - GIPS-H
MONITOR DOMUS PILOT
ACTIVE DOMUS PILOT
1"PIPE
1" CL150 RF OUTLET
2ND STAGE CONDITIONS
Fluid : TBA
Inlet Pressure : 5 TO 19.6 Bar
Outlet Pressure : 3 Bar
Maximum Flow : TBA SCMH
REVISIONS
00
DO NOT SCALE
IF IN DOUBT ASK
THIRD ANGLE PROJECTION
TITLE:-
P & I DIAGRAM
FUEL HYDROGEN GAS TRAIN 2 STAGE
CL2500 / CL150 (IP)
PROJECT REF: FT22-114
THIS DRAWING IS THE EXCLUSIVE PROPERTY OF FT PIPELINE SYSTEMS CONTROLS LIMITED AND THE ACCEPTANCE OF THIS PRINT CONSTITUTES AGREEMENT THAT IT WILL BE TREATED AS A CONFIDENTIAL DOCUMENT. IT IS NOT TO BE COMMUNICATED, DISCLOSED, COPIED OR PUBLISHED EXCEPT AS EXPRESSLY AUTHORISED IN WRITING BY
SCALE NTS UNLESS STATED
DIMENSIONS IN MILLIMETRES UNLESS STATED
DRAWN P.HOLLAND DATE 17/06/2022
CHECKED DATE
APPROVED DATE
CAD REF. NO.
DRAWING NO. FT22-114-01-001
Form FT A2 Issue 0

A4. Technical Information Sheet - *First Quality Multi*

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Britain's Brick Specialists

Product Technical Information Sheet

Freshfield Lane
First Quality Multi

Configuration:	Frogged Clay Facing Brick				
Size:	215 x 102.5 x 65 mm				
Dimensional Tolerance:	T2		Dimensional Range:	R1	
Density (net):	1690	Kg/m³	Density Tolerance:	D1	
Density (gross):	1460	Kg/m³			
Compressive Strength:	27	N/mm²	Compressive Strength Category:	II	
Water Absorption:	12	%	Initial Rate of Water Absorption:	2.5	
Durability Category:	F2		Soluble Salts Category:	S2	
Thermal Conductivity: (P=50)	0.45	W/m.K	Thermal Resistance P=50:	0.23	m².K/W
Thermal Conductivity: (P=90)	0.51	W/m.K	Thermal Resistance P=90:	0.20	m².K/W
Water Vapour Permeability Coefficient:	5/10		Bond Strength (fixed value):	0.15	N/mm²
Dangerous Substances:	Not Applicable		Void Percentage:	6 - 11	%
Recycled Content:	0	%	Reaction to Fire:	Class A1	

Clay bricks are manufactured and supplied to relevant clauses of BS EN 771-1.

Declarations of performance, environmental and other policies can be found on the company website: www.mbhplc.co.uk. Further information is available via our sales department on 0844 931 0022 or email sales@mbhplc.co.uk

Technical data correct at the time of issue. Please order a sample for accurate representation of product.

Issue Date: 18/11/21

A5. First Quality Multi Required Aesthetics

A6. Technical Information Sheet - *Hampshire Stock Light Multi* Bricks

MICHELMERSH
Britain's Brick Specialists

Product Technical Information Sheet

Michelmersh™

Hampshire Stock Light Multi

Configuration (EN 771.1):	Frogged Clay Facing Brick		Dimensions:	215 x 102.5 x 65 mm	
Compressive Strength:	>= 6	N/mm²	Dimensional Tolerance:	T1	
Compressive Strength Category:	II		Dimensional Range:	R1	
Freeze/Thaw Resistance:	F2		Water Absorption:	=< 18	%
Soluble Salts Content Category:	S2		Initial Rate of Water Absorption:	5	kg/m².min
Reaction to Fire:	Class A1		Dangerous Substances:	N/A	
Thermal Conductivity (P = 50):	0.41	W/m.K	Thermal Resistance (P = 50):	0.25	m².K/W
Thermal Conductivity (P = 90):	0.47	W/m.K	Thermal Resistance (P = 90):	0.22	m².K/W
Void Percentage:	7 - 13	%	Net Dry Density:	1600	kg/m³
Water Vapour Permeability Coefficient:	5/10		Gross Dry Density:	1400	kg/m³
Bond Strength (fixed value):	0.15	N/mm²	Density Tolerance:	D1	
Quantity per Pack:	495		Recycled Content:	0	%
Product Weight:	2.02	kg	DoP common root reference code:	–MM65FAB–	
Products per Square Metre:	60				

Clay bricks are manufactured and supplied to relevant clauses of BS EN 771-1.

Declarations of performance, environmental and other policies can be found on the company website: **www.mbhplc.co.uk**. Further information is available via our sales department on 0844 931 0022 or email **sales@mbhplc.co.uk**.

Technical data correct at the time of issue. Please order a sample for accurate representation of product.

Issue Date: 22/09/2022