Low Carbon Hydrogen Supply 2 Competition Tetronics Hydrogen Plasmolysis Final Report

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CHECKED			
Name	**Responsibility**	**Signature**	**Date**
David Deegan	Chief Technical Officer		03/06/2025

APPROVED			
Name	**Responsibility**	**Signature**	**Date**
John Conway	Head of Project Management		04/06/2025

Executive Summary

The aim of this project was to scale up a Hydrogen Plasmolysis prototype with a power input of 18kW to an end-to-end plant capable of producing pure hydrogen at a rate of 7 kg/h with a plasma power input of up to 300kW.

Tetronics' Hydrogen Plasmolysis (THP) novel approach offers a potentially more efficient and flexible alternative to traditional green hydrogen production methods. THP compares favourably with current best in class electrolysers, offering

- Higher Efficiency enabling H2 cost of circa $1-2/kg with optimisation and scale up.
- Feedstock flexibility – including saltwater, ammonia and methanol.
- Extended operational life (99% performance after 30+ years).
- Tolerance to power outages – rapid start stop and system turn down.

Plasma technology typically has a lifespan of 30+ years, depending on the operating conditions and maintenance practices and compares very favourably with the best-in-class electrolyser alternatives, providing a significant cost of ownership advantage over the life of the plant. The technology's potential for integration with renewable energy sources further strengthens its competitive positioning.

Tetronics Technologies Limited (TTL) have developed a plant which could be used as a benchmark for further scale up and commercialisation of the technology which would fit into the roll-out plan. The technology offers flexibility to build commercial scale systems of different sizes to meet specific customer requirements, but TTL are targeting 1MW followed by 10MW plants in the first instance as this is where the anticipated market demand is set.

The THP modules were designed to be integrated with upstream raw material preparation and delivery equipment and a downstream purification system to enable a hydrogen product compliant with ISO 14687 – Hydrogen Fuel Quality to be produced.

Plasmolysis produces hydrogen through both the electrical and thermal breakdown of water or another hydrogen carrier such as methanol or ammonia. The thermal breakdown of water (or another hydrogen carrier) occurs through the direct interaction between the feedstock and the plasma arc. The reaction may be aided by the catalytic effect of plasma through the production of free electrons, photons and free radicals which reduce the overall energy requirement for the breakdown of the molecule compared with its traditional thermal breakdown alone.

The Technology Readiness Level (TRL) achieved during the prototype phase was 6 and a further aim of the project was to raise the TRL to 7. Unfortunately, whilst there was some hydrogen produced during the project, it was not produced at the efficiency level originally targeted by the project team mainly due to the inability of the water feedstock to penetrate through and into the hottest area of the plasma arc thus preventing the key breakdown reactions to occur.

Throughout the project phases of design evolution, procurement and manufacturing of the system, TTL learned many lessons and through the commissioning and testing phases were able to determine specifically why those reactions did not occur and more importantly through subsequent Computational Fluid Dynamics (CFD) modelling were able to evolve the design further such that the issues could be resolved with modifications to the current design. This report covers the design evolution of the system, the procurement and manufacturing of the system as well as detailing the key risks and issues associated with the project. It also covers the trials results and offers up the reasons why the project was unsuccessful and what could be done to correct the design and achieve the original targeted outcomes.

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Glossary of Terms

ALARP – As Low As Reasonably Practicable

API – American Petroleum Institute

ATEX – Atmosphères Explosibles

BEIS – Department for Business, Energy and Industrial Strategy

BWT – Best Water Technology

CFD – Computational Fluid Dynamics

COTS – Commercial off-the-shelf

DC – Direct Current

DESNZ – Department for Energy Security and Net Zero

DSEAR – Dangerous Substances and Explosive Atmospheres

ERD – Equipment Requirements Document

EPR – Environmental Permitting Regulations

HAC – Hazardous Area Classification

HAZID – Hazard Identification Study

HAZOP – Hazard and Operability Study

HPBM - Hydrogen Production Business Model

ID Fan – Induced Draft Fan

IED - Industrial Emissions Directive

IO – Input and Output

KPI – Key Performance Indicator

LCHS - Low Carbon Hydrogen Standard

NFPA – The National Fire Protection Association

NPI – New Product Introduction

NZIP – Net Zero Innovation Portfolio

P&ID – Piping and Instrumentation Diagram

PLC – Programmable Logic Controller

PL – Performance Level

PPS – Plasma Power Supply

PSA – Pressure Swing Adsorption system

RAM – Risks and Methods

RFP – Request for Proposal

RFQ – Request for Quotation

R&D – Research and Development

SBRI - Small Business Research Initiative

SCADA – Supervisory Control and Data Acquisition

THP – Tetronics' Hydrogen Plasmolysis

TRL – Technology Readiness Level

TTL – Tetronics Technologies Limited

VLE – Vapor Liquid Equilibrium

QGA - Quadrupole Gas Analyser

1 Background

1.1 Company Background

Tetronics Technologies Limited (TTL) is a company based in Swindon, Wiltshire specialising in DC plasma arc technology. With over 60 years of experience in plasma systems and having installed 97 references across the world, TTL is the world leader in plasma technology.

TTL have developed plasma solutions for various sustainable applications including valuable metal recovery, waste vitrification and gas reformation. Recently, TTL have also identified the use of plasma as a tool to help companies achieve decarbonisation goals. This can be achieved by replacing natural gas burners with plasma burners and through the production of hydrogen, a clean fuel, via the action of plasma which has been the focus of this project.

The number of staff currently employed at TTL is 30.

1.2 Project Background

Tetronics Hydrogen Plasmolysis (THP) is a novel hydrogen production technology which utilises the thermal and catalytic properties of plasma to crack or split a molecule containing hydrogen (hydrogen carrier) to produce hydrogen gas.

THP has the potential to compete with current state-of-the-art hydrogen production technologies such as electrolysers and steam-methane reformation. The use of plasma to produce hydrogen has several advantages such as the flexibility of feedstocks and various grades of water (pure, waste, salt), fast response and turn-up times and the avoidance of the use of exotic or critical raw materials such as platinum group metals.

This project aimed to scale up the 18 kW ‘Prototype’, funded in the Phase 1 BEIS Hydrogen Supply 2 Competition, to a 300 kW system known as the ‘Commercial Demonstrator’. The design built on the successes and learnings from the Prototype and incorporated TTL’s experience in plasma devices to enable the scale up of the system. In doing this the project aimed to take the TRL of THP from 6 to 7.

2 Project Overview

2.1 Aims and Objectives

The overarching aim of the project was to scale up the Hydrogen Plasmolysis Prototype by incorporating the lessons learned from that system to design and build an end-to-end plant which can produce pure hydrogen at a rate of 7 kg/h with a plasma power input of up to 300 kW.

Therefore, the key objectives of the project were,

- Successfully demonstrate the technology at a commercially relevant scale.

- Demonstrate how Plasmolysis can be integrated into wider plant equipment to produce hydrogen of a suitable purity for end use.
- Generate operational data to refine calculations for the hydrogen production rates, energy use, efficiency and the levelized costs of production which offer a better KPI comparison to current state-of-the-art systems.
- Produce operational and compliance data to support the licensing of a commercial facility.
- Develop a plant which can be used as a benchmark for further scale up and commercialisation of the technology which fits into Tetronics' roll-out plan.
- Use the system as a benchmark to develop a longer-term operation technological risk and methods (RAM) assessment for a commercial facility.

2.2 Schedule

The contract was commenced on 7th March 2023. The original schedule was to complete the project by 31st January 2025. Following a formal and agreed change request, the end date of the project was extended to end of June 2025 for agreement of the final report.

2.3 Deliverables

A list of key deliverables is described under Section 6.1. These cover all aspects of the project as TTL moved its way through the phases of its New Product Introduction (NPI) Process.

2.4 Financial Information Including Baseline Cost and Actual Spend

TTL received a Small Business Research Initiative (SBRI) Contract for the value of £3,664,744.92 from DESNZ. By end of the project TTL has incurred an actual spend of £4.1m. The overspend was covered by TTL own shareholder investment and funding.

3 Design Considerations and Challenges

3.1 System Design

The design and development of the Commercial Demonstrator system followed Tetronics' New Product Introduction (NPI) process. The NPI process is a staged and gated process which runs throughout the project life cycle and across all design phases, concept design, detailed design and final design. Following each milestone a formal review of the design took place to agree that it was of a sufficient maturity before proceeding to the next design phase. Each design phase was supported by the generation of engineering documents including piping and instrumentation diagrams (P&ID), engineering drawings and safety studies.

These phases were:

- concept design
- preliminary design
- detailed design
- final design

The Commercial Demonstrator is designed to have plasma power input of 300 kW. This scale was chosen so that the system would be comparable with commercially available electrolyser systems and act as an iteration of the design before a larger 1 MW or greater system. The 300 kW was achieved through the combined power of six 50 kW cells which were of a scale to allow for additional understanding of various scale-up parameters prior to designing higher power cells in future plants.

The plant was installed at TTL's trials facility (Arc Lab) in Swindon. The system was installed mostly as a standalone system, although some aspects of the plant utilised existing infrastructure on site to facilitate the installation and the overall capital spend on the project. These existing utilities included nitrogen and argon storage tanks, cooling water system and the existing 'off gas system' which includes a thermal oxidiser and induced draft fan. The 'off gas system' was used to safely handle the hydrogen produced in the plant by controlled combustion rather than release to atmosphere or to store it. This system would not be expected to be part of a commercial plant which would be producing hydrogen for use or storage where a bespoke design would be developed.

The THP modules were designed to be integrated with upstream raw material preparation and delivery equipment and a downstream purification system to enable a hydrogen product compliant with ISO 14687 – Hydrogen Fuel Quality to be produced. The target purity of the hydrogen was Type 1 Grade E hydrogen as laid out in Table 1 and Table 2. This would suit applications such as hydrogen burners or power systems which have been identified as suitable applications for the THP technology.

Table 1: Hydrogen Grade and Category Definitions

Type	Grade	Category	Applications
I Gas	E	1	Hydrogen based fuel; High efficiency / low power applications
		2	Hydrogen based fuel; High power applications
		3	Gaseous hydrogen; High power / high efficiency applications

Table 2: Type I Grade E Hydrogen Product Specifications ISO 14687

Constituents (assay)	Type I, Grade E		
	Category 1	Category 2	Category 3
Hydrogen fuel index (minimum mole fraction)	50%	50%	99.9%
Total non-hydrogen gases (maximum mole fraction)	50%	50%	0.1%
Water (H_2O)	Non-condensing at all ambient conditions		
Maximum concentration of individual contaminants			
Total hydrocarbons expect methane (C_1 equivalent)	10 µmol mol^{-1}	2 µmol mol^{-1}	2 µmol mol^{-1}
Methane (CH_4)	5%	1%	100 µmol mol^{-1}
Oxygen (O_2)	200 µmol mol^{-1}	200 µmol mol^{-1}	50 µmol mol^{-1}
Sum of nitrogen (N_2), argon (Ar) and helium (He) (mole fraction)	50%	50%	0.1%
Carbon dioxide (CO_2)	Included in total non-hydrogen gases		2 µmol mol^{-1}
Carbon monoxide	10 µmol mol^{-1}	10 µmol mol^{-1}	0.2 µmol mol^{-1}
Total sulphur compounds (S1 equivalent)	0.004 µmol mol^{-1}	0.004 µmol mol^{-1}	0.004 µmol mol^{-1}
Formaldehyde (HCHO)	3.0 µmol mol^{-1}	0.2 µmol mol^{-1}	0.2 µmol mol^{-1}
Formic acid (HCOOH)	10 µmol mol^{-1}	0.2 µmol mol^{-1}	0.2 µmol mol^{-1}
Ammonia (NH_3)	0.1 µmol mol^{-1}	0.1 µmol mol^{-1}	0.1 µmol mol^{-1}
Halogenated compounds (Halogen ion equivalent)	0.05 µmol mol^{-1}	0.05 µmol mol^{-1}	0.05 µmol mol^{-1}
Maximum particulate concentration	1 mg kg^{-1}	1 mg kg^{-1}	1 mg kg^{-1}
Maximum particle diameter	75 µm	75 µm	75 µm

The end-to-end plant included the following sub-systems in the design:

- mains water to Type II pure water system
- services distribution manifolds (cooling water, feedstock, nitrogen)
- six off THP cells forming a singular containerised module

- product gas purification system (compressor and pressure swing adsorption system)

The core of the technology was designed to fit within an ISO container as shown in Figure 3.1. This demonstrated the ability of the technology to fit within a small footprint to facilitate installation within an existing industrial plant or even in offshore settings coupled with wind turbines.

The whole plant layout is shown in Figure 3.2 and identifies the remaining plant equipment not included in the container (power supply, compressor and pressure swing adsorption unit) which were connected through various cable and pipe runs. Photographs of the compressor and the pressure swing adsorption system are shown in Figure 3.3.

Figure 3.1: ISO container containing the THP modules and distribution manifolds

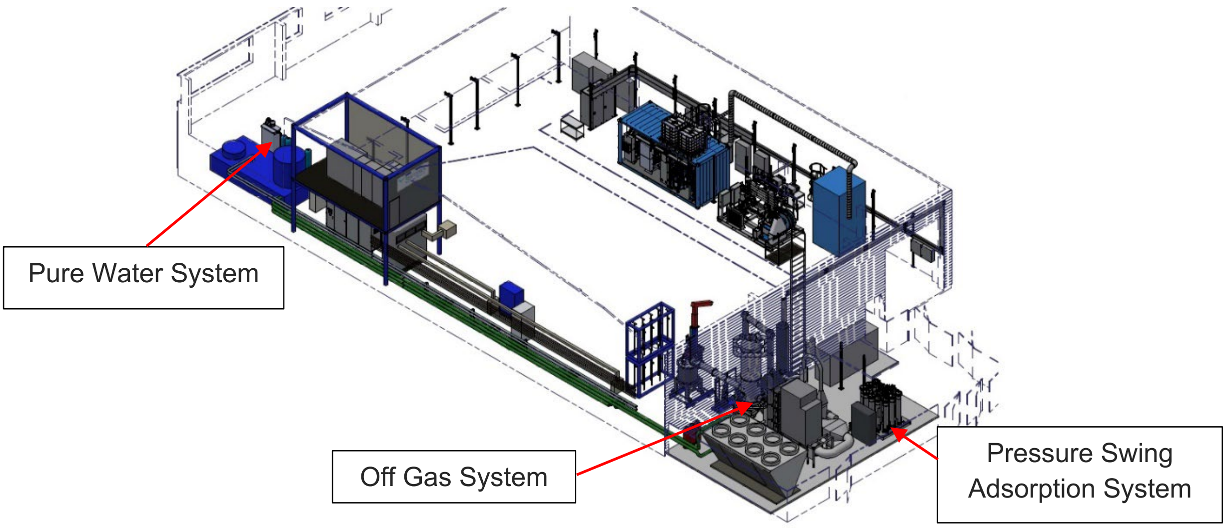

Figure 3.2: Commercial demonstrator Arc Lab layout

Figure 3.3: Compressor (left) and pressure swing adsorption unit (right)

Six 50 kW THP cells combine to produce a total input of 300 kW (Figure 3.4). Each cell contains a thermolysis chamber and an electrolyser. The design of the module evolved from the Prototype through the learnings of its operation and better understanding of the reaction mechanism.

Plasmolysis produces hydrogen through both the electrical and thermal breakdown of water or another hydrogen carrier such as methanol or ammonia.

The thermal breakdown of water (or another hydrogen carrier) occurs through the direct interaction between the feedstock and the plasma arc. The heat and light energy from the plasma arc breaks apart the feedstock molecules to produce hydrogen and by-products reflecting the composition of the feedstock. The reaction may be aided by the catalytic effect of plasma through the production of free electrons, photons and free radicals which reduce the overall energy requirement for the breakdown of the molecule compared with its traditional thermal breakdown alone.

As an electrical circuit is used to form and maintain the plasma arc, the current can also be used to drive electrolysis reactions to form hydrogen from water within an electrolyser. In this way, the flow of electrons moves from the plasma to the electrolyser to drive the electrolysis reactions and back around the circuit. This would produce additional hydrogen, improving the process efficiency. The balance of power used to maintain the plasma arc and in electrolysis can be measured using individual voltage meters across each part of the circuit.

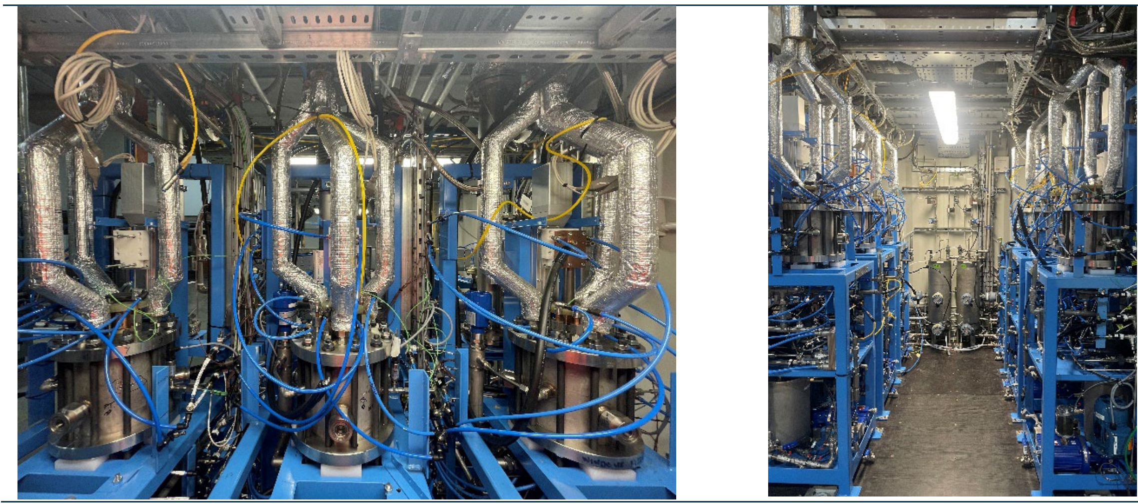

Figure 3.4: Rows of THP modules in the ISO container

The basic layout of the THP module is shown in Figure 3.5. This provides an illustration of how the electrical circuit works within the system and how that translates to the module design. The action of the plasma in the thermolysis chamber produces the bulk of the hydrogen (design point is 90%) whilst the electrolysis aspect provides an additional ‘boost’ of hydrogen production. The system could be operated with only the thermolysis chamber in operation or both systems in operation depending on the desired configuration or requirement of a facility.

The Prototype system operated with the plasma arc acting on a bath of electrically conductive water (KOH containing) and included both a cathode and anode which intended to promote both the thermolysis and electrolysis reaction mechanisms within the same vessel. Through the operation of the Prototype and additional trial work at the beginning of this project, it became apparent that to improve the electrolysis aspect of the process, multiple electrolysis cells would be required to produce any meaningful contribution to hydrogen from the system (due to the low operational current and Faraday’s Laws of electrolysis).

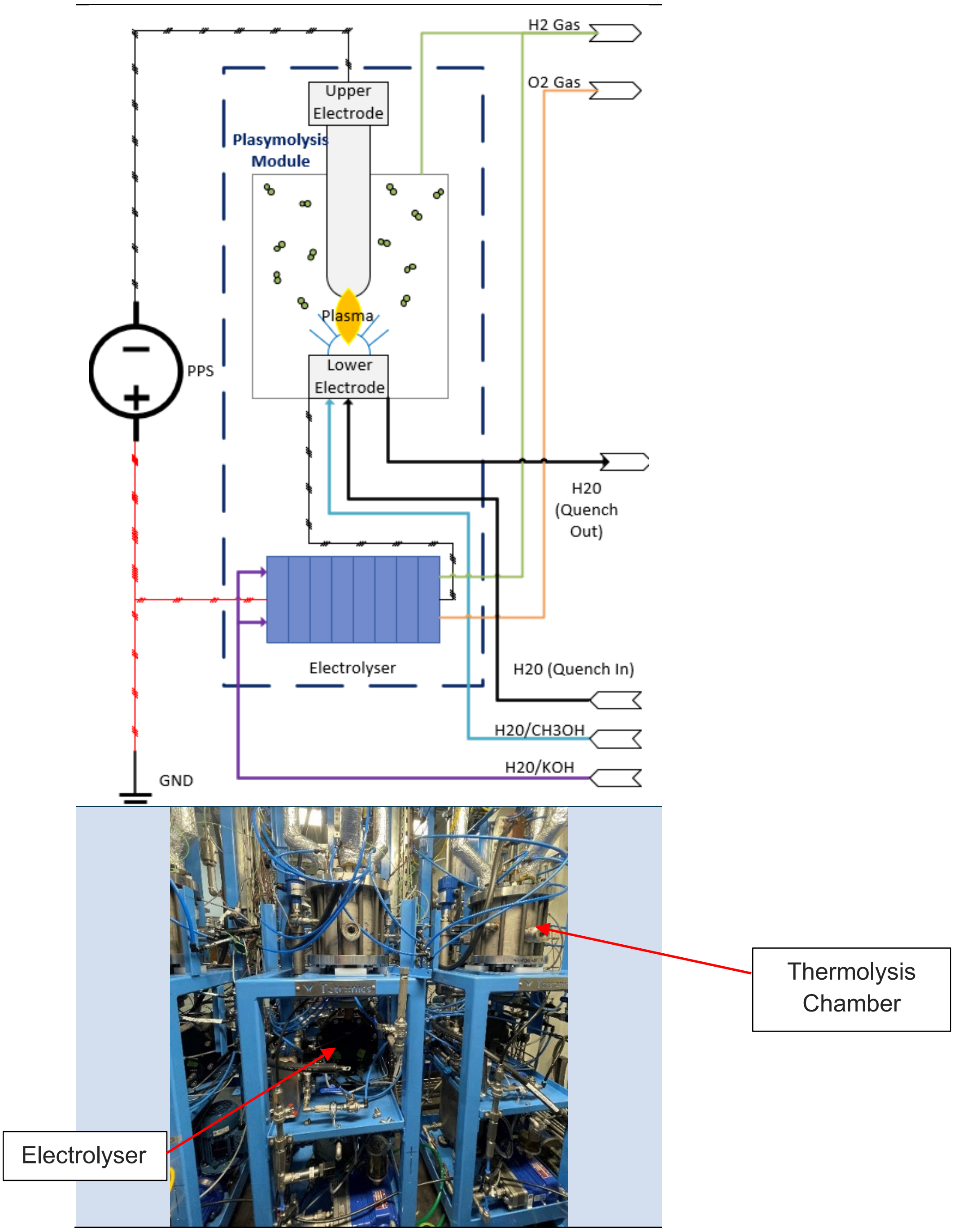

Figure 3.5: Schematic of the THP module electrical circuit (top) and a model view of the THP module showing the main components (bottom)

In addition, the action of the arc on the bath produced significant voltage fluctuations where resistive product gases would form around the arc leading the arc to flicker to locations with lower resistance which led to some degree of plasma instability. The formation of product gases around the arc also limited the mass transfer of reactants to the arc and thereby limited reaction kinetics. To solve these two problems, an alternative feedstock delivery mechanism was employed in the Commercial Demonstrator. This delivery mechanism took the form of a spray / mist where the feedstock was sprayed into and around the arc to enable it to react but also promote the movement of the products away from the arc as they were formed.

The THP thermolysis chamber design consisted of various components which are described in the following section.

3.1.1 The Chamber Vessel

The thermolysis chamber is a pressurised vessel designed to contain the plasma arc reaction and product gases and fluids within it whilst withstanding the thermal and chemical environment thereby avoiding excessive corrosion and thermal degradation. The vessel's material of construction is stainless steel 316 which has good hydrogen compatibility to avoid degradation caused by hydrogen embrittlement. The thermal integrity of the vessel was maintained through cooling rings within the chamber, as well as the action of the water spray to keep the chamber temperature below 390°C (less than 75% of the autoignition temperature of hydrogen, which is reported as 585°C in the Basic considerations for the safety of hydrogen systems standard, ISO/TR 15916:2015) and below a temperature that which would cause heat deformation of the steel. The vessel design contains features which were intended to maximise the thermal energy such as thermal heat reflectors which aimed to reflect heat towards the feedstock zone.

The design parameters based on the expected operating conditions for the vessel are shown in Table 3.

Table 3: THP Thermolysis Chamber Design Parameters

Parameter	Unit	Value
Minimum working temperature	°C	25
Maximum working temperature	°C	390
Maximum operating pressure	barg	3
Chamber design pressure	barg	3.3
Chamber hydrostatic test pressure	barg	4.5

Although the design pressure (reflective of the normal operating pressure) was 3.3 barg, CFD modelling was undertaken to test the design at the transient high pressures which would be experienced during an explosion. The results showed that the cell design was robust enough to withstand the conditions in an explosion (a function of pressure and time) without fragmentation or failure of the materials. A CFD image in Figure 3.6 shows the maximum deflection of the vessel during an explosion simulation with a maximum explosion pressure of 42 MPa was only 0.1 mm and so demonstrating it would safely survive the event.

The vessels also have three view ports on the side walls which enabled either a camera to be placed to view operations inside the vessel or to place the optical spectrometer receiver unit to monitor the optical emissions from the plasma, reactants and products.

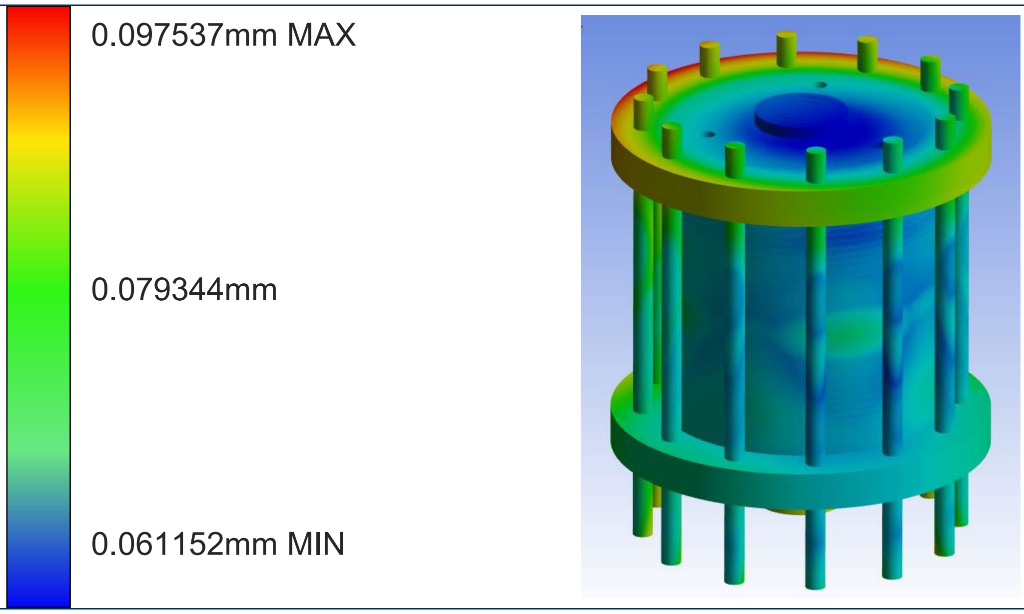

Figure 3.6: CFD model of the deflection of the vessel during a simulated explosion

3.1.2 Plasma Electrodes and Actuation System

The plasma torch system and actuator were designed to be able to provide fine control over the plasma arc initiation and movement during operation.

In the initial design of the Commercial Demonstrator, the feedstock and the quench water added to the chamber around the anode, by pumping through concentric annular orifices and directly into the plasma arc.

In this design, to initiate plasma, the upper and lower electrodes needed to be moved close together to almost touch and then once the arc was established, they would be moved apart from each other. This was accomplished by attaching the upper electrode to an actuation system which could be remotely controlled via the Supervisory Control And Data Acquisition (SCADA) operator. As such fine control was required, an actuator with micron precision was selected for the design.

Nitrogen was used in this design as the plasma gas. The flow of the nitrogen was controlled by mass flow controllers located on a distribution manifold in the ISO container. This enabled the nitrogen flow rate to be quickly changed remotely and as required for the different operational stages such as purging or plasma operation. The use of nitrogen was a change from the Prototype system where argon was used.

In the early stages of the project, different plasma gases were trialled in the Prototype system. These included argon, nitrogen and hydrogen. As argon is a monatomic gas, it is typically easier to form a plasma with and produces an arc with a lower voltage than diatomic molecules such as nitrogen and hydrogen. However, the trials demonstrated that plasma could be operated and maintained easily with both nitrogen and hydrogen, and if the power supplies were specified to be able to meet the voltage demand of the system a higher operational voltage would be acceptable. Hydrogen was initially preferred to be used as the plasma gas as it would result in a product gas from the thermolysis chamber, but for a trial system the supply of hydrogen in bottles or containers would be prohibitively expensive. A commercial plant could have a closed loop recirculation stream of hydrogen which could be used, and this may have positive implications on the total plant equipment requirement by making purification of the gases produced simpler. A decision was made to use nitrogen as the plasma gas based on the output of a review of the various hydrogen purification technologies available on the market. Typically, nitrogen is easier to remove from hydrogen than argon and so required a less complex purification technology or route. For example, the pressure swing adsorption suppliers indicated that a two-stage system would be required to ensure that argon would be removed to the required levels to meet the desired ISO standard hydrogen product. The base cost of nitrogen is also less than argon and so its use reduces the operating cost of the system as it is also used as the purge gas for the system.

A commercial facility would operate with a plasma gas which would reflect the optimal conditions for that site. It may be that the system has an existing nitrogen or argon infrastructure which would support the use of one over the other which is normal for other plasma systems installed by Tetronics.

During the commissioning phase of the project, several issues arose with the operation of the LaB_6 (Lanthanum Hexaboride) plasma electrodes, which resulted in a redesign of the cell utilising an existing TTL product: 38 mm twin torch anode and cathode. The twin torch system was implemented to increase stability and longevity of the plasma or plasma device. With this change the plasma start mechanism also changed from a ‘touch start’, which can be contaminating to ‘high frequency’ arc start. However, this meant that argon had to be used as the plasma gas to facilitate the start and nitrogen was added later via the cathode. This meant the resulting product gas from the chamber contained argon and nitrogen. Therefore, the downstream purification of the product will need to be optimised for a mixed argon / nitrogen gas product.

The change to the 38 mm design also introduced a change into the water spray mechanism. This was done to maintain the integrity of the proven plasma torches and to avoid excessive changes to the known design, at least as a proof of concept. Despite the redesign of the spray delivery into the cell, this did not have an impact on the upstream feedstock or quench delivery system.

The plasma torch, in principle, had known functionality and provided more protection utilising a conventional metallic electrodes within shrouding nozzles.

3.1.3 Feedstock and Quench Delivery Systems

Pure water was used for both the quench and feedstock water. However, the purpose of the quench water was to act as a means to rapidly cool the product gases as they formed, to limit any back reactions and improve the hydrogen yield. The quench water also diluted the oxygen produced from the thermal splitting of water to keep its concentration below the limiting oxygen concentration for hydrogen. This was to avoid the formation an explosive atmosphere in the chamber where the greatest risk of ignition was perceived to be (around the plasma arc). Both the feedstock and quench systems were designed to be recycled and therefore the energy and material used with higher efficiency.

In the initial design, the quench flow pattern could be controlled by manipulating water supply flowrate through alteration of the pump speed. The feedstock and the quench water were added to the chamber around the anode, by pumping through concentric annular orifices and directly into the plasma arc. However, once the 38mm torch design was introduced, the feedstock was added to the system via an alternative mechanism of spray nozzles that were independent of the torches.

3.1.4 Product Gas Handling System (heat exchanger and drain)

The gases produced inside the thermolysis vessel exit through a heat exchanger which is designed to reduce the output gas temperature to around 25°C for integration with downstream plant equipment. The heat exchanger is vertically mounted to enable condensate to drain back to the quench storage tank.

Downstream of the heat exchanger a flow meter is present to monitor the output flow from each vessel, which when combined with gas composition analysis, provides granular production rate efficiency for each vessel. On this flow line, each vessel had a gas sampling line which was connected to a mass spectrometer. Two mass spectrometers were installed which allowed for analysis of individual process lines to occur which was facilitated by using a rotary sampling valve which could be programmed to analyse each sample line in turn.

A view of the gas handling systems for each THP thermolysis chamber is shown in Figure 3.7.

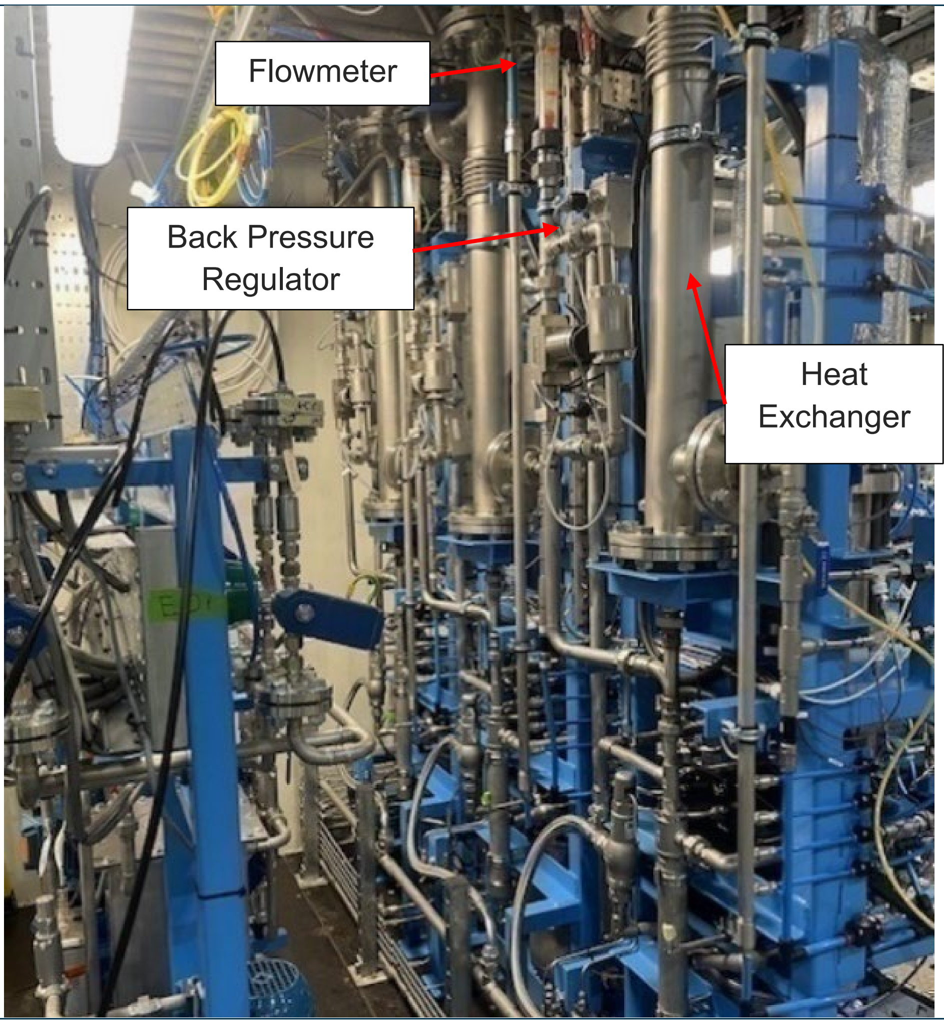

Figure 3.7: THP chamber gas handling system

As alluded to in the above descriptions, the various plant subsystems upstream of the THP module were designed to serve the various components in the system i.e.

- mains to pure water generation
- cooling water manifold and pump set
- plasma gas (nitrogen) manifold and pipe work
- feedstock delivery manifold and pumps

Downstream of the THP modules the following plant equipment was installed:

3.1.5 Gas Combination Manifold

This equipment combines the output of the THP modules into a single stream. This manifold includes two solenoid valves which act to direct the product gas either directly to the off-gas system for burning, or (based on safety based permissive being achieved) to the compressor and pressure swing adsorption system for purification.

3.1.6 Purification System

The purification unit selected for the plant was a pressure swing adsorption unit. This unit consists of nine vessels filled with an adsorption media. Pressurised process gas is sent to a vessel and the non-hydrogen impurities in the gas are adsorbed onto the media whilst the hydrogen travels freely up and out of the vessel. The input to the vessel is closed and it is then depressurised to release the adsorbed molecules into a 'tail gas' or waste gas stream. The use of multiple vessels allows for a continuous operation with some being pressurised as others are depressurised.

The compressor increases the pressure of the product from the THP modules from 1.8 barg to 16 barg which is the optimum pressure for the pressure swing adsorption unit.

The pressure swing adsorption unit produces a hydrogen product stream >99.9% hydrogen purity and a tail gas stream containing the various contaminants produced from the THP unit. The flow rate of each stream is monitored to enable mass balance accounting of the product gas and coupled with gas analysis via the mass spectrometer determine total plant efficiency and hydrogen yield.

3.1.7 Off-Gas Handling System

This is the existing TTL off gas system which is used to fully oxidise the hydrogen (and other by-products) as they are produced to avoid emissions, accumulation or on-site storage. In this system, a plenum vessel was added to combine all the outputs from the system into a single stream to simplify the integration with the existing thermal oxidiser (combustion chamber).

A total plant flow sheet is shown in Figure 3.8 showing the main features of the plant.

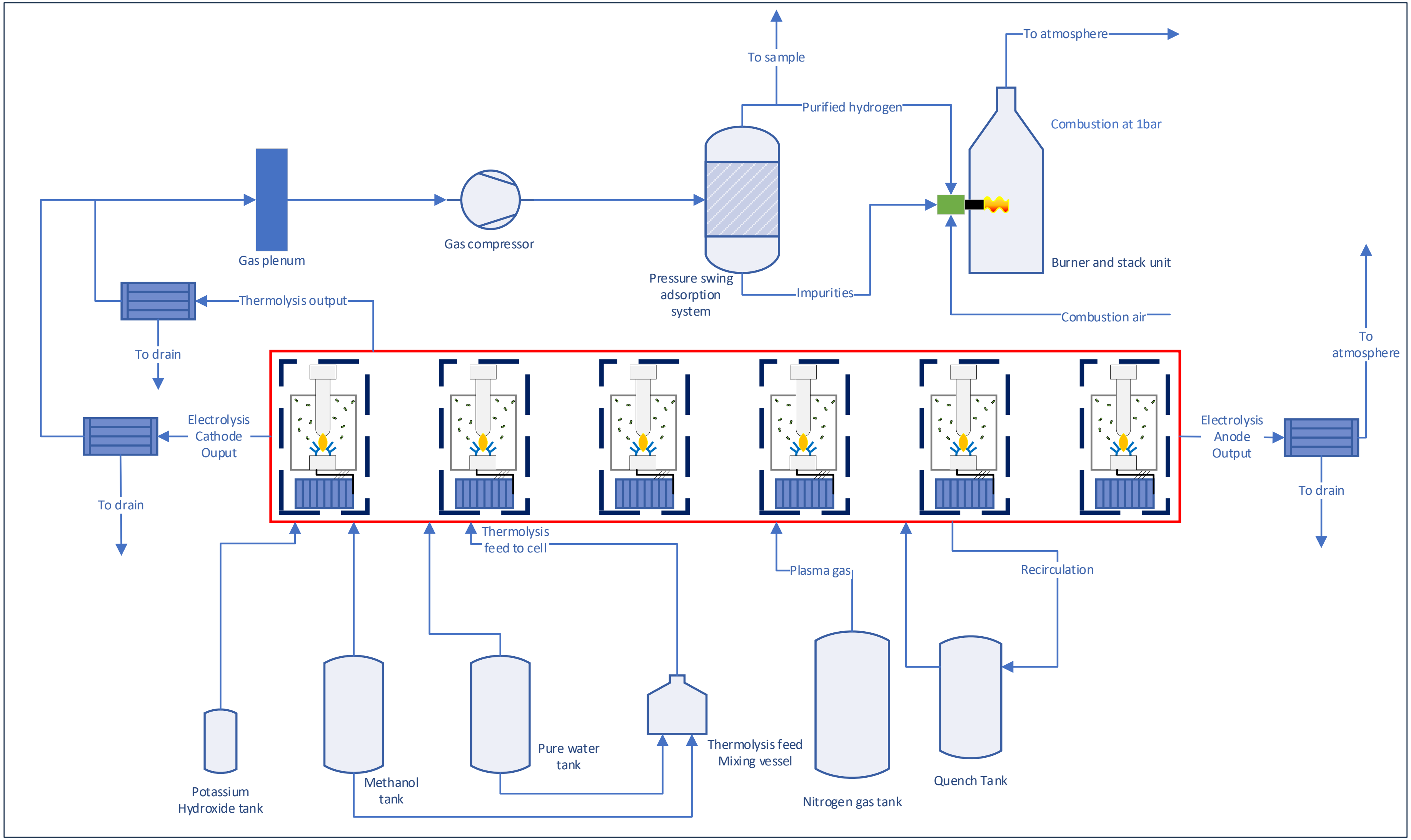

Figure 3.8: Basic plant flow sheet

3.2 Challenges and Verification Activities

3.2.1 Plant Integration Challenges

3.2.1.1 Compressor

The integration of the THP cells with wider plant equipment was a key challenge in the design of the plant and this affected the operating parameters of the thermolysis chambers.

Almost all commercially available hydrogen purification technologies operate at pressure and the operating pressure is dependent on the technology type (pressure swing adsorption system, membrane systems, etc.), but is typically greater than 10 barg.

A key challenge for Tetronics was to understand how this delivery pressure could be met, and two options were assessed. The first option was to use a compressor unit to compress the THP chamber output and the second option was to operate the thermolysis chambers at the required pressure.

Operating the thermolysis chamber at a pressure >10 barg was seen to be a technical risk due the lack of experience with a pressurised plasma meaning the characteristics of pressurised plasma arcs particularly their voltage and stability were unknown. In addition, the operating pressure would increase the complexity of the chamber vessel design as it needed to be rated to at least 1.5x the operating pressure to satisfy design standards. There was also an additional layer of complexity with the handling of hydrogen and safety design considerations around explosion mitigation. These factors would increase the cost of the chambers and introduce significant technical risks.

However, there was a procurement challenge in finding a compressor which was able to operate with the operating conditions of the Commercial Demonstrator. The compressor needed to compress the output of the thermolysis chamber to 16 barg so that the gas would be at the optimum pressure for the pressure swing adsorption purification unit. For many suppliers the scale of the process was too small or the suction and discharge pressures not suitable for their compressor designs (too low pressures in both cases).

Most available compressors required their inlet pressure to be greater than ambient (0 barg) and so this meant that the thermolysis chamber would need to be pressurised to some degree to enable integration. The selected compressor required an inlet pressure of 1.4 – 1.8 barg and so considering the pressure drop between the chambers and the compressor, the thermolysis chambers would require operation at 3 barg.

Despite the compressor being an additional capital cost, it would allow the thermolysis chamber to be operated at more moderate pressures where plasma is better characterised reducing technical risks. Therefore, the decision was made to operate with a compressor.

There was still a residual risk on the operation of plasma in a pressurised environment and the characterisation of the arc would need to be determined empirically. However, the operational pressure at 3 barg was considered manageable and would offer an opportunity to test plasma under pressure which could act as a stepping stone to operate it at greater pressures in future designs. This may facilitate the integration of the THP modules with purification systems without the need for a compressor and so cut the capital cost of the plant. An assessment of the overall capital cost with a compressor vs pressurised vessels would need to be made to identify the most cost-effective solution.

During the operation of the system for the project, the plasma was able to be operated without hinderance at pressures up to 3 barg. When operating at pressure, the operating voltage increased marginally which had some benefit in achieving target power inputs into the system, no detrimental consequences were noted.

3.2.1.2 Purification System

A key benefit of the THP system is that it has great flexibility to be able to operate with different feedstocks. However, for the Commercial Demonstrator, obtaining a purification system which was flexible enough to purify the hydrogen containing different contaminants from different feedstocks i.e. oxygen from water or carbon dioxide from methanol.

The pressure swing adsorption unit was chosen as the system which had the greatest flexibility when compared to technologies such as membrane separation systems. However, the specification of the purification system was challenging due to the lack of certainty about the likely concentrations of some contaminants in the process gas with a key one being oxygen. The data produced from the Prototype system suggested that the oxygen concentration would be low, but there was a discrepancy between these data and the calculated oxygen concentration based on a stoichiometric reaction of water to produce hydrogen and oxygen. If the oxygen concentration was closer to the calculated value, then the product gas mixture would be a flammable mixture which made most commercially available purification technologies unsuitable for handling the gas mixture.

The issue was resolved in this system by introducing on-line oxygen monitoring and a by-pass line to avoid gas mixtures unsuitable for purification being processed through the pressure swing adsorption unit. TTL engaged with the NZIP Acceleration Support Programme to initiate a study into suitable purification technologies for flammable gas mixtures which may be more suitable for this system in future plants. The study identified some technologies such as vacuum pressure swing adsorption and cryogenic separation. However, it is likely that future technological development may need to be undertaken in partnership with a hydrogen purification technology supplier to develop a unit which is bespoke for the THP system.

3.2.2 Hydrogen Safety Challenges

Producing hydrogen introduced design challenges which defined equipment and instrumentation specifications and requirements as well as operational modes and procedures to ensure safe operation to avoid explosions or fires. These requirements and specifications were identified and developed from the outputs of a DSEAR study which included all relevant plant equipment.

The approach to safety is discussed in Section 3.3, but the outputs of the DSEAR study defined the hazardous area classifications in the plant (ATEX zones) which in turn defined the ATEX specification of the instrumentation and equipment located within those zones.

In some instances, there was a procurement challenge in finding instrumentation (valves, regulators, sensors etc.) with the correct ATEX rating (Zone 0, Zone 2, etc.) and which were also able to operate in the process conditions (temperature, composition and pressure). Although producers of valves and instrumentation are developing equipment to operate with hydrogen, this equipment was more expensive when compared with parts not designed for hydrogen. The requirement in some areas of the plant to have intrinsically safe equipment (ATEX Zone 0) meant that the cost of these units was in some cases significant. During the design phase, TTL undertook a value engineering exercise to attempt to simplify the design where possible with an aim to reduce the overall cost of equipment. Although this was possible in some areas, the need to generate good quality and granular data to monitor the process meant that significant instrumentation was required. However, on a commercial facility this would not necessarily be the case.

The requirement for intrinsically safe equipment was due to the possibility that during the thermolysis of water, both hydrogen and oxygen would be produced in concentrations resulting in a mixture within the flammable range. To manage such an occurrence, possible sources of ignition needed to be removed, which could in part be achieved by using intrinsically safe equipment (anti-static, low temperature, low electrical current, etc.). However, some process equipment could not be sourced to be intrinsically safe, and the compressor and purification system (pressure swing adsorption system) could not be designed to handle a flammable mixture. Therefore, a by-pass line was introduced and designed to be implemented if the oxygen level was above a maximum permissible oxygen concentration (defined by the pressure swing adsorption supplier).

3.2.3 Plasma Torch Challenges

Although TTL have developed numerous plasma torch designs, the specific conditions under which each operate present different challenges in different applications. Plasma torches must withstand the intense heat of the plasma arc and so be cooled sufficiently to avoid failure, but in this application the torch also had to withstand an aggressive chemical environment with water, hydrogen and oxygen which can attack the materials of construction.

After experiencing problems with the initial design, an alternative apporach was implemented. The alternative design was pursued to improve the performance and longevity of the plasma torch. The alternative design involved undertaking some small modifications to an existing 38 mm twin torch design which was thought to be more suitable to allow for sustained plasma operation.

The plasma torch in operation images are shown in Figure 3.9. A positive development for TTL was being able to demonstrate the ability to establish plasma at 3 barg pressure. Plasma could be started at pressure which simplified the operation of the vessel.

The positive outcome of the pressurised plasma operation provides some indication that in future iterations of the design it may be possible to increase the operating pressure further which may improve plant integration or at least operational flexibility.

As well as operating at pressure, the 38 mm torch design allowed for a stable plasma to be reliably established which was able to withstand water admission. It was also able to operate with different flow rates of plasma gas, mixtures of gas and different arc lengths. This provided a baseline to operate and optimise a single THP cell.

Figure 3.9: Plasma images inside the thermolysis vessel

3.2.4 Verification Studies

The Commercial Demonstrator used the Prototype system as a baseline for its design. This included using empirical output composition data from the Prototype trials to develop the process flow diagram, expected compositions and mass and energy balance.

However, as the design of the thermolysis chamber evolved, the empirical data from the Prototype became less reflective of the likely outputs from the Commercial Demonstrator. Therefore, a complementary thermodynamic model was developed to provide theoretical data to support the design. This meant that there was uncertainty regarding some process parameters and outputs which would have to be validated during the initial operating trials of the Commercial Demonstrator.

To perform this validation additional instrumentation was incorporated into the design to generate these data. Much of this instrumentation would not necessarily be needed on a commercial plant but was included to ensure that sufficient data were generated to support the further development of the technology.

The parameters and techniques used to monitor the plant, and its performance are described Sections 3.2.4.1 to 3.2.4.4.

3.2.4.1 Hydrogen Production Efficiency (kg/kWh)

Measured by combining several pieces of data from the product gas produced and comparing that to the energy input into the process at both a module level (plasma power supply) and a total plant level.

The gas output composition was measured using a mass spectrometer at different sampling points (immediately at the exit of the thermolysis unit, at the gas combination manifold and after purification). The gas flow rate was measured using flow meters at the outputs of the thermolysis and electrolysis units and after the pressure swing adsorption unit.

3.2.4.2 Hydrogen Purity

Measured using a mass spectrometer at the exit to the pressure swing adsorption unit and prior to purification at the gas combination manifold which provided information on the recovery efficiency across the purification system.

3.2.4.3 Energy Efficiency and Cooling Requirements

Measured by comparing the power input into the plasma process via the plasma power supply in kW and measuring the heat absorbed by the cooling water at the various cooling points in the system (chamber, torch, etc.). Through determining the ‘heat load’ of the cooling water system via $Q=mC_p\Delta T$, the cooling requirements of the system can be validated and compared to the power input to produce an efficiency value.

3.2.4.4 Plasma – Feedstock Reaction Mechanism

An optical spectrometer has been installed in the system to generate data to help further understand the reaction mechanism between the feedstock and the plasma arc. The optical spectrometer can be used to identify reaction products, free radicals and plasma species which may provide some information regarding the 'plasma effect'.

3.3 Hazard Studies

During the design of the plant, safety studies were undertaken as necessary and at different phases of the design maturity. The studies undertaken followed Institute of Chemical Engineers (IChemE) hazard study guidance as well as specific studies which were required due to working with hazardous atmospheres (DSEAR).

Through the engineering design phase of the Commercial Demonstrator, the safety studies were undertaken to identify and reduce / eliminate risks in the process by applying a hierarchy of controls and ALARP (as low as reasonably practicable) principles. The studies included:

- Development of a 'Basis of Safety' document which defined the fundamental safety risks in the process and identified the key regulations and standards applicable to the plant and equipment.
- Hazard Studies 1 and 2 (Hazard Identification (HAZID)) undertaken on 28th June 2023.
- Hazard and Operability Study (HAZOP study) undertaken between the 25th and 29th September 2023.
- Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) risk assessment undertaken on 31st August 2023.
- Development of a Hazardous Area Classification (HAC) diagram as a DSEAR output identifying the type and extent of HAC zones.
- Development of a Pressure Control Philosophy document which defined the engineering and process requirements for the control and management of an explosive mixture in the process.
- Third party explosion containment computational fluid dynamic (CFD) modelling.
- Development of Standard Operating Procedures for the process.
- Third party review of all safety documents and operating procedures for the minimisation of the risk of an explosion.

The safety studies were designed to reduce or eliminate risks of the process through the development of a hierarchy of controls to ensure the system was safe by design. The studies generated actions which reflected the requirement to develop the hierarchy of controls to achieve ALARP and provided guidance on the functionality and purpose of the master control system for the system i.e. alarm levels, automatic interventions, interlocks and so on.

The use of third-party consultants was deemed necessary to facilitate the DSEAR study and validation of the design for managing and avoiding an explosion. This was to ensure that the approach Tetronics developed was robust and compliant with industry best practice.

As the design of the Commercial Demonstrator matured, there was a concern surrounding the generation of hydrogen and oxygen gases within the thermolysis chambers. To reduce the risk for a catastrophic event, levels of protection were incorporated into the design which were supported by the available regulations and standards including:

- NFPA 68 Standard on Explosion Protection by Deflagration Venting (2023)
- NFPA 69 Standard on Explosion Prevention Systems (2023)
- API 520 Sizing, Selection and Installation of Pressure-Relieving Devices
- API 521 Pressure-Relieving and Depressurising Systems
- Pressure Equipment (Safety) Regulations 2016

The levels of protection in the design relating to explosion mitigation in the thermolysis chamber were two-fold. They were to firstly avoid the formation of a flammable mixture through purging and dilution and secondly to avoid an ignition through the management of temperature and other ignition sources.

The breakdown of the safety features in the plant regarding hydrogen explosions are as follows.

- Purging the equipment prior to operation and shut down with nitrogen.
- Using water in the thermolysis chamber to control the oxygen concentration and ensure it is below the minimum oxygen concentration.
- Use of water in the thermolysis chamber to ensure the product gas temperature is below the autoignition point of hydrogen.
- Automatic process interlocks if temperature / pressure exceed critical alarm levels.
- Automatic feedstock interlock if the diluent water stream stops.
- Avoidance of ignition sources within the chamber and downstream equipment through the use of intrinsically safe equipment, correct earthing to avoid static and cleaning routines to avoid friction.
- Oxygen concentration analysis prior to compression and purification to avoid a flammable mixture being sent to this equipment.
- Presence of water and nitrogen in the thermolysis chamber to act as an explosion suppressant if above controls failed.

- Confirmation through modelling that the chamber will not fragment and therefore contain an explosion if above controls failed.

Other safety considerations around the plant design which were studied and addressed through the HAZID and HAZOP studies included the following.

- The operation of electrically live components (plasma torches, power supplies, etc.).
- The requirement for system thermal management to ensure the integrity of devices such as the plasma torch, thermolysis vessel and electrolyte temperature.
- Operation with high pressure water.
- Operation with high pressure gases (nitrogen and process gases).
- Containment of hazardous chemicals (methanol and potassium hydroxide) for safety and environmental concerns.
- General access and operability issues.

3.4 Control Logic

The control system developed by Tetronics was designed to be the interface between the operational performance of the equipment and the Master PLC.

The system is controlled by an Allen Bradley Compact Logix PLC system using Ethernet IO networks which allows the PLC to communicate to all nodes and third-party PLC systems in the plant.

Through this communication, all logic control functions with the plant are managed by the Master PLC which sends and receives commands and information about plant status and operation from the individual local nodes.

Each sensor and instrument on the plant has a unique alpha / numeric code and ‘tag’ which formed the basis of creating an I/O schedule for the plant. This enabled each sensor to be easily identified, and its function understood by the operator and used as a point for the control system’s code to monitor to enable / disable interlocks or take an action, i.e. create set points for alarms and interlocks.

The Commercial Demonstrator operates with a combined hardware and software safety system using proprietary safety relays for hardware interaction and the PLC for lower-level software functions.

The plant contains PL rated safety relays which are activated by emergency stops located around the plant. The activation of an emergency stop results in the stoppage of the process (plasma extinguishing, feedstock stopping), but maintains safety critical systems with the primary aim of ensuring that no residual flammable gas remains in the system i.e. the ID fan remains in operation and normally open valves allow purge gas to enter the cell in emergency conditions including a power failure. In such a case the ID fan and the fugitive emissions system are operated by a back-up generator.

The use of emergency stops and ‘hardware’ safety features are not automatically controlled and act as a ‘last resort’ when situations arise and are dependent on human observation. The ‘software’ strategy uses the PLC software to continuously monitor plant operations and uses a hierarchical structure of alarms to inform, warn and finally stop elements of the process.

To facilitate the monitoring of the plant status, alarms for the various sensors and instruments are defined and are arranged into two classes: critical alarm and non-critical alarms. The two alarm levels give operators the chance to rectify ‘out-of-specification’ issues without completely stopping the process.

Non-critical alarms are defined as those that provide a warning or information that the operator should be made aware of, but do not represent an immediate action requirement. They may be indicative of intermittent process instability or a progressive change occurring in the system, which will require attention at some point in the future.

Examples of non-critical alarms include:

- Plasma torch low gas flow rate.
- High temperature on cooling circuit loop.
- Low cooling water supply pressure.

Critical alarms are deemed as situations that cannot be safely recovered from by the automation system and a controlled and automated stop will be performed.

Examples of critical alarms include:

- Low-Low level on cooling system tank – indicates dangerously low level of cooling water in the buffer tank.
- Low-Low cooling water flow – may indicate cooling system failure.

In addition to the automated control system, some aspects of the plant use a combination of automatic software interlocks and an operator intervention to add another layer of safety. An example of such a system on the plant is the operation of the by-pass / purification line which is in place to avoid flammable gas mixtures to be sent to the purification system. The oxygen level is monitored by a laser gas analyser (MN233_OX001) and the route for the gas to travel down either the by-pass or purification lines is controlled by the action of two solenoid valves. The default position is for the gas to travel down the by-pass line until the oxygen levels have been determined to be safe via the analyser. The control system will monitor the oxygen concentration and compare it to a set point and will only enable the solenoid valve for the purification system to be opened if the oxygen concentration is below this set point. However, this valve will not automatically open and requires the operator to confirm that they are satisfied that the oxygen concentration is correct and may use a secondary measurement technique to confirm the laser analyser value (mass spectrometer). The operator would then open the solenoid valve via the SCADA after it has been 'unlocked' by the control software. If during the use of the purification line, the oxygen concentration raises above the set point, the control system will automatically close the purification solenoid valve and open the by-pass line without the operator's intervention.

The interface between the control system and the operator is the SCADA system. This allows the operator to receive plant information, receive notification of alarms and make process interventions or control plant equipment.

In the THP system a new SCADA system was designed and programmed to operate the plant. Each subsystem has its own SCADA page displaying the relevant information and the operator is able to navigate between pages as required. It also allows the operator to initiate various automatic control or operational sequences which were designed to facilitate operation especially when multiple THP modules are in operation. The SCADA system was also designed to be able to store and export process data to allow for various process data analysis to be undertaken offline. Data can also be plotted into on-line trends which provide a visual description of the condition of the process and whether it is operating stably or whether an intervention is required.

Examples of the SCADA screens are shown in Figure 3.10, Figure 3.11 and Figure 3.12.

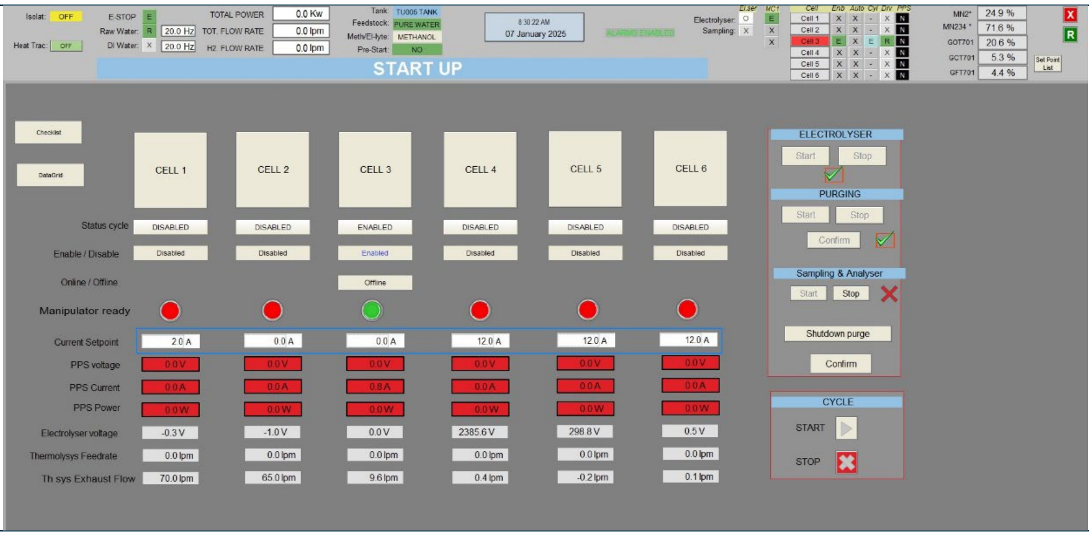

Figure 3.10: Cell overview SCADA screen

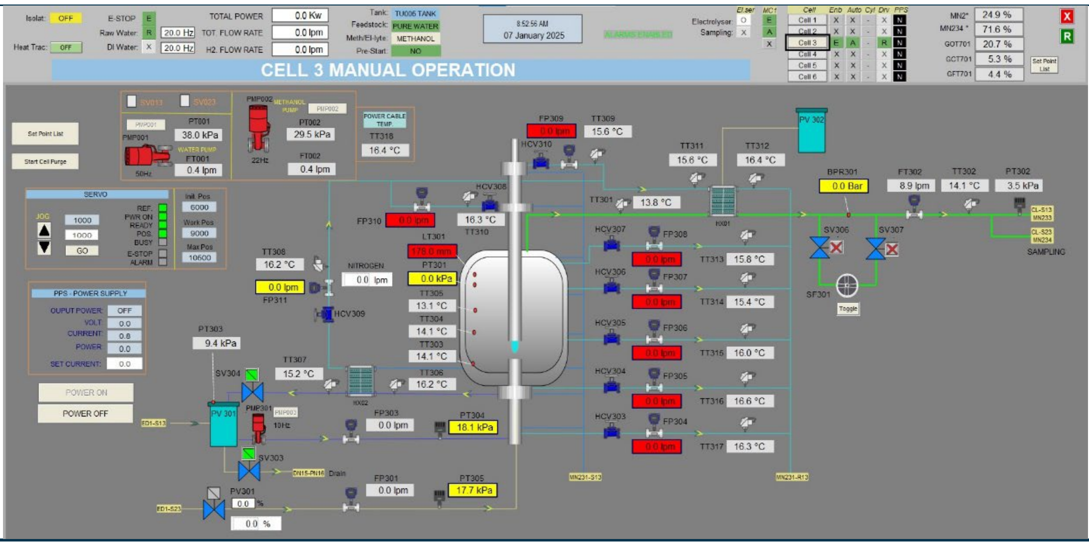

Figure 3.11: Cell 3 SCADA screen

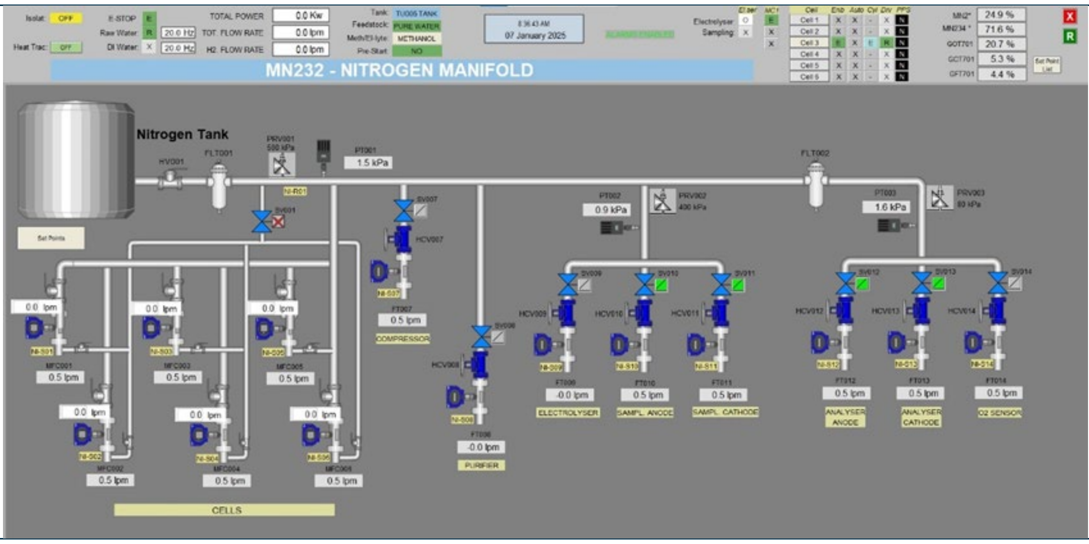

Figure 3.12: Nitrogen manifold SCADA screen

3.5 Selection of Technical Components

To select and purchase technical components, TTL’s engineering and procurement departments worked together to define equipment specifications, identify potential suppliers and evaluate proposals.

The approach to procurement of items differed depending on whether the items were parts of equipment which would be built / assembled in-house at Tetronics, items which were to be designed by Tetronics, but built by a third party or large items which were designed and manufactured by a third party to specifications defined by Tetronics.

For items to be designed and manufactured by a third party, Tetronics wrote an Equipment Requirements Document (ERD) which detailed the performance requirement of the system (process flow parameters, pressure rating, temperature requirements, purification requirements etc.) and provided relevant engineering drawings such as piping and instrumentation drawings (P&ID).

The ERD was then sent to relevant suppliers, and the returned proposals were then assessed by the engineering team for the technical content and the project management / procurement team for delivery timescales and contractual information.

The supplier and Tetronics would agree product acceptance test criteria to validate the performance of the equipment either prior to dispatch or on site to ensure the performance is as per the requirements.

For items which Tetronics were to build or assemble on-site the engineering team would develop a bill of materials for a particular system or sub-system. This contained the relevant information for the procurement team to source the item such as material specifications, size etc. and often a preferred supplier.

Items were purchased in line with the project budget which had been generated for each sub-system (defined as a work package) and the required time scales or the project schedule which was, at times, challenging particularly for some large items such as the compressor.

3.6 Procurement and Fabrication Activities

The first steps in the process were to identify through Tetronics New Product Introduction (NPI) procedure design reviews whether Equipment, Assemblies, Sub-assemblies and parts were to be procured as;

- Design & Make – Supplier designs, details and makes equipment.
  - Tetronics provides:
    - High level concept outlined in a technical specification (Equipment Specification Document)
- Detail & Make – Supplier provides design details and makes equipment
  - Tetronics provides:
    - Developed design detailed in an Equipment Requirements Document (ERD)
- Make to Print – Supplier fabricates/ machines / assembles parts to drawing(s).
  - Tetronics Provides:
    - Detailed manufacturing / assembly drawings.
- Commercial off-the-shelf (COTS) – Tetronics specifies commercially available equipment / parts.

When the type of supply was agreed Tetronics Procurement team then followed Quality Procedure for the procurement of equipment, assemblies, sub-assemblies and parts.

Suitable suppliers / sub-contractors where possible were identified from Tetronics approved suppliers list and RFP / RFQ issued where possible to a minimum of 3 suppliers.
However, due to the R&D nature and technical complexities of this project where there were no suitable approved suppliers for one off specialist equipment or materials the Engineering Design Team identified suppliers and sought quotes with procurement providing commercial and expediting support.

When the bids / quotes for high value equipment / systems i.e. Gas Purification were received, these were collated and reviewed by Engineering, Projects and Procurement for:

- Technical Compliance
- Commercial terms
- Lead Time

Where costs were above the project work package budget these had to be approved by the project manager or CEO before the contract / order could be placed.

Upon completion of the review and contract negotiations, the contract / purchase order was issued to the successful bidder.

Key Equipment Supply – RFP / RFQ Issued Included:

Water Purification and Storage System – Design & Make

- RFP issued to 2 suppliers
    - 21443-R0A Technical Specifications issued with RFP.
- Technically compliant proposals received from 2 companies
- Purchase order placed on 10th December 2023 with Best Water Technology (BWT).

Hydrogen Gas Compressor – Design & Make

- RFP issued to 8 suppliers, 4 of which declined to bid and 2 of which did not meet technical requirements.
    - 1180-22-ERD002-R1 Technical Specification issued with RFP.
- Technically compliant proposals received from 2 companies
- Contract placed on 11th October 2023 with Fluitron Inc. based on lead time.

Hydrogen Gas Purification System - Design & Make

- RFP issued to 6 suppliers, 5 of which declined to bid.
    - 1180-22-ERD003-R5 Technical Specification issued with RFP.
- Technically compliant proposal received from
    - Ivy's (Xebec) Canada.
- Contract placed on 3rd October 2023.

Distribution Systems – Detail & Make

Comprising Cooling Water, De-ionised (DI) water, Hydrogen Gas, Natural Gas

- RFP was issued to 2 suppliers and one bid was received from a Tetronics approved supplier used on several other projects as they could detail and make all water and gas systems. The other could only detail & make water systems.
    - 1180-17-ERD001-R2 issued with RFP
- Technically compliant proposal received from
    - Denco Lubrication Ltd. UK
- Contract placed on 20th December 2023.

Plasma Power System (PPS) – COTS

- Single sourced as determined by Engineering Department because the power supplies were used on original demonstrator.
- Technically compliant proposal received from
    - IDRC Hong Liu Limited, Taiwan
- Purchase order placed on 1st March 2024.

Plant Electrical Control system - Detail & Make (In House Assembly & Test)

Comprising 14 off Electrical control panels required to control and operate the installed equipment.

- All components required to assemble electrical control panels were COTS.
- Tetronics approved suppliers used including Routeco, Parmley Graham, RS Components.
- Panels were assembled and tested in house.

Plasma Torch (Anode & Cathode) – Parts supplier Make to Print. (In House Assembly & Test)

- RFQs were issued to suppliers based on material type (e.g. metals or composites), machining and fabrication specifications.
- RFQ and drawing packs were issued to 15 suppliers.

3.7 Consents and Planning Applications

Tetronics reviewed the environmental permitting requirements for the Arc Lab facility in Swindon to ascertain whether further consents or permits would be required for the Commercial Demonstrator.

As a Research and Development facility, Tetronics operates under an Exemption to Permit from the Environment Agency. The exemptions in EPR Schedule 1, Part 1, Paragraph 3 only apply to activities that would otherwise fall within Part 2 of Schedule 1 of EPR 2016. The previous THP (Prototype) trials fell below the Part A

(1) Section 5.1 waste incineration activity thresholds and Part B criteria. This position remained unchanged for the Commercial Demonstrator as it still fell below these parameters. Section 1.2 (gasification, liquefication and refining activities) did not apply as the hydrogen produced was fully oxidised on-site.

Tetronics has been advised by the Environment Agency that our activities are to be regulated by Swindon Borough Council as a Small Waste Incineration Plant (SWIP), Schedule 13 of EPR 2016. The Environment Agency has advised that if Tetronics can demonstrate that it can meet the Industrial Emissions Directive (IED) Chapter IV Article 42 exemption, the Schedule 13 of EPR 2016 would not apply. Tetronics wrote to Swindon Borough Council to confirm that we meet the Article 42 exemption and a SWIP permit for the operations will not be required.

4 Demonstration Study

4.1 Overview of the Demonstrator

Tetronics Hydrogen Plasmolysis (THP) aspires to be an innovative Green Hydrogen technology. It uses plasma to enhance hydrogen yields taking it a step beyond conventional electrolysis. Plasma is produced when a gas is ionised using electrical energy and traditionally emits intense heat and ultra-violet light which promotes chemical reactions and the decomposition of molecules, including water.

The core of THP technology is a plasmolysis cell containing a cathode and an anode, this is complemented by an electrolyser that is in electrical communication. In plasmolysis the thermal decomposition of water is promoted by the plasma generated that remains physically separate from the working electrolyte of the electrolyser. Therefore, hydrogen is produced by both the electrochemical and thermal breakdown of water resulting in a higher hydrogen yield compared to electrolysis alone. Beyond this, plasma was envisaged to enable novel reaction pathways to occur through the production and participation of highly reactive free radicals and ions at temperature. The design of the plasmolysis cells evolved during the project and Figure 4.1 summarises the evolution of the design:

Phase 1: BEIS	Phase 2: DESNZ #1	Phase 3: DESNZ #2
Key Cell Design observations: • Submerged central (solid) and circumferential (mesh) anode. • Plasma operates between the torch and the conductive electrolyte bath (30% w/w KOH (aq)). • Hot and corrosive environment limited electrode life and caused excessive component corrosion. • The conductive solution caused issues with electrical isolation, leading to problematic stray side arcing. • Bath turbulence impacted stability limiting potential scale up. • 18 kW cell.	Key changes: • Re-designed & reduced the size of the anode and cathode torches. • Transitioned from using a conductive bath to utilizing pure feedstock for cooling the torches, feeding it directly into the plasma arc. This approach proved to be overly complicated, unreliable, and resulted in the anode overheating. • Cell scaled up to 50 kW	Key changes: • Utilises proven 38mm Anode & • All torch elements are electrically isolated and improved water-cooled. • Cell remains at 50 kW.

Figure 4.1: Diagrammatic representation of the technological development of plasmolysis

In Phase 1 (BEIS), Tetronics developed a prototype THP system that demonstrated hydrogen being produced from plasmolysis. The system was built and commissioned by Tetronics, and trials were undertaken to demonstrate the working system, examine the impacts of variables and generate hydrogen production data.

The Phase 1 data show that Plasmolysis is able to achieve a high hydrogen yield per unit energy. The thermodynamic minimum net energy required to form hydrogen from water is 39.39 kWh/kg H_2 (equivalent to 25.4 g H_2/kWh$_e$) (Rehman, Wameath, Majeed, & Zimmerman, 2013). Under optimal conditions, when operating with a bio-methanol-solution electrolyte, a specific hydrogen production rate of 25 – 28 g H_2/kWh$_e$ (equivalent to a specific gross energy requirement 36 – 40 kWh$_e$/kg H_2) was achieved. This was approximately a 10% improvement in efficiency beyond the theoretical minimum and significantly better (40% improvement) than current range of reported commercial performance of a PEM cell (47 – 66 kWh/kg H_2) (IRENA, 2020). Subject to commercial demonstrator validation, THP was considered to represent the most energy efficient means of producing green hydrogen currently known.

Various instrumentation installed on the Phase 1 system measured the outputs of the process and monitored intermediate reactions or species generated by the plasma itself. The results highlight the contribution of both the electrochemical breakdown of water and the products of the plasma-induced breakdown as both hydrogen (H and H_2) and hydroxyl (OH-) emissions can be seen in the spectra, Figure 4.2. These data demonstrate the divergence of the technology away from traditional Faradic electrolysis. The results are also supported by results published in academic literature from previous researchers (Mizuno, et al., 2005).

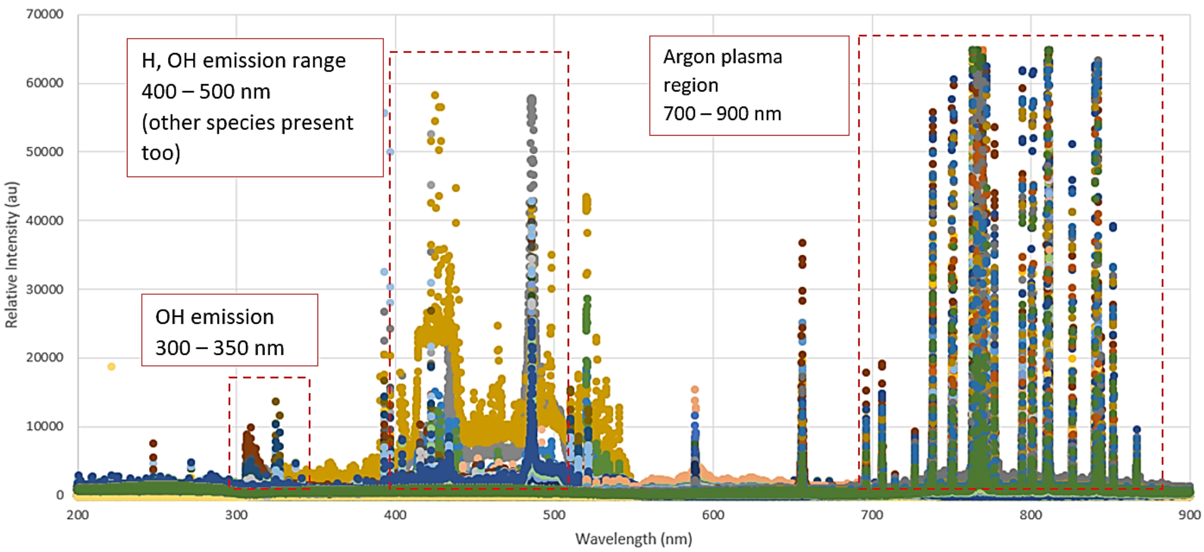

Figure 4.2: Qualitative optical emission spectrometer data of species formed around the plasma

Prior to the Prototype, the laboratory investigations into plasma-induced hydrogen production had only been achieved with a low power input and over short experimental time scales. Although these experiments demonstrated the proof of concept, they lacked the technology for consistent operation and longevity. At this point, the Technology Readiness Level (TRL) of THP was TRL 4.

The Prototype demonstration system, at the end of Phase 1, moved THP to TRL 6 as Tetronics designed and tested a system with a power input of up to 14 kW_e, a significantly larger scale than previous laboratory work. The design incorporated Tetronics expertise in developing plasma technology and resulted in a system capable of maintaining consistent operation. Plasma instability was common for previous researchers whose experiments lasted around 10 seconds. The trials demonstrated the consistent production of hydrogen, under what would be close to operational conditions due to the online addition of electrolyte and water, balancing their consumption with reference to gas formation justifying the TRL increase.

The design of the process as well as the integration of Tetronics DC plasma torch technology demonstrated THP at a significant scale whilst resulting in good hydrogen yields and production rates. This supported the technology as being a new and competitive method of Green Hydrogen production.

To build upon the success of the working system built in Phase 1, Tetronics scaled the THP technology to a power input of 300 kW_e in Phase 2, Figure 4.1. Based on the results of Phase 1, the 300 kW_e system would produce approximately 7 kg/h of Green Hydrogen. This will enable an assessment of the performance, efficiency, and cost of the technology at a scale aligned with commercially available electrolysis systems.

The commercial demonstration plant was described in Section 3.1. These cells were configured to showcase the technology as an end-to-end or ‘turnkey’ system boosting THP’s credentials as a commercially viable and marketable technology. Importantly, the plant was configured to demonstrate the integration of the plasmolysis cell with wider plant equipment for future commercialisation of the technology, essentially the design and operation of the cells/module had to complement the downstream systems to produce a consistent hydrogen product of the required specification (ISO 14687) for the intended end use.

The Phase 2 demonstration system was configured to facilitate an increase in the TRL as it would demonstrate and validate the technology as an end-to-end solution, if successful raising the TRL to 7. The scale being similar to some commercially available electrolysis systems with the ability of modules to be combined to achieve 1 - 10 MW_e, within the general range of the currently installed project’s capacities (IRENA, 2020). The engineering development of the demonstrator required staff for the operation and maintenance of the facility, invaluable in determining the training and skill requirements for the operation of a commercial system and the supporting infrastructure, as well as empirically defining the basis of maintenance cycles based on wear or consumption data.

Increasing the TRL for the technology complemented Tetronics' commercial roll-out plan, which includes a step to a 1 MW system as well as a 10 MW system. These systems represent the two strands of plants envisioned for the technology, one being large scale plants producing hydrogen for network distribution and the other being smaller scale plants for onsite hydrogen production.

In May 2023, to further inform the design of the Phase 2 facility, Tetronics upgraded the Prototype facility to improve its operability and to provide more accurate data, sustained and wide-ranging performance data. A non-exhaustive summary of the improvements is:

- Alumina coating and material substitution to avoid side arcing.
- Modification of the cathode and anode off gas pipe routing and sampling lines, with the addition of a tube in tube heat exchanger, to aid gas flow and sampling for performance measurement.
- Utilise a Hiden Quadrupole Residual Gas (QRG) mass spectrometer for gas analysis.
- Installation of a submerged nickel central electrode within the electrolyte bath.
- The plasma gas was changed between argon, hydrogen and nitrogen.

Overall, the outcome of the equipment improvements was favourable and enhanced hydrogen production rates and efficiencies were achieved for both water-based and methanol-based electrolytes. The central electrode had the most profound effect on the performance with water, however corrosion or by product deposition was found to be problematic. The central electrode also reduced the operational voltage of the plasmolysis rig reduced from 600 – 700 V to 400 – 450 V which was impactful on power deposition, but the arc was stabilised through operation at higher currents. A clear correlation was achieved between plasma current/power and hydrogen production rate. The impact of plasma gas changes is summarised in Table 4.

Table 4: Summary of Plasma Operating Conditions with Different Plasma Gases

Plasma gas	Open circuit voltage for start (V)	Operating voltage (V)	Notes
Argon	1,500	~450	Plasma can be easy to maintain and operate with low voltages.
Nitrogen	1,500	600 – 800	Plasma could be started easily, but arc very difficult to maintain and tests were cut short due to instability (plasma appeared to be submerged frequently but longer arcs could not be sustained).

Plasma gas	Open circuit voltage for start (V)	Operating voltage (V)	Notes
Hydrogen	1,500	700 – 1,000	Plasma started easily, voltages considerably higher than argon voltage fluctuations frequent. Rig was operated for 10 mins without stoppage (controlled time).

Overall hydrogen productivity was improved with increases in current/power, methanol addition and the central electrode. The concentration of hydrogen in the product gas also increased with methanol. All of these observations lead to the conclusion that in the prototype cell the formation of hydrogen is driven primarily by the thermolysis element of plasmolysis, and the lower temperature and energy thresholds, result in performance on methanol being superior. Importantly, and in all cases a high hydrogen concentration (10 – 45%) was not complemented with a high oxygen concentration, which was an anomaly and counter to thermodynamic predictions. Upon further examining the plant data the amount of condensate recovered from the off-gas system was found to be a lot more significant for water than methanol, which was taken as a strong indication that reversion reactions were a lot more prevalent for water, than methanol; an occurrence had to be managed in the Commercial Demonstrator (Phase 2). Back reactions are evidenced by the presence of water in the product gas of the cell and the non-stoichiometric hydrogen oxygen and hydrogen carbon monoxide composition which was produced. In summary when the BEIS rig was operated twice with a bath of electrolyte, outputs were >10 g/kWh (equivalent to > 100 kWh/kg H_2) with water and the voltages achieved were >600 V.

Conceptually, for the Commercial Demonstrator, the process intention was to maximise the impact of thermolysis whilst complementing it with conventional electrolysis. To achieve this the thermolysis feedstock was initially introduced into and around the plasma via the integrated anode electrode arrangement. Referencing numerous historic spectroscopic assessment this proximity was intended to allow the hydrogen carrier feedstock to experience the extreme temperatures required to undergo thermal breakdown.

Downstream of the cell, to further minimise the occurrence of back reactions, which will reduce the overall efficiency of the THP system a heat exchanger was configured to cool the gas promptly and to dry it ahead of the compressor.

Due to the disparity between theory and results with the Prototype work, Tetronics' thermochemical and cell operational models assumed the water needed to reach between 3000 – 4000°C for thermolysis to occur. This was known to be conventional but conservatively robust. The models include the VLE diagram and the impact of pressure on equilibrium, the unlikely back/reversion reactions and NOx formation (which occurs with a lot more significant oxygen). Better performance was anticipated through the action of the plasma, 'the plasma effect', which facilitates this breakdown through photocatalytic activity, delivery of free electrons and free radical generation. Reaction rates are high in plasma systems due to thermal activation and the localised temperatures experienced around the arc. However, the complexities of the 'plasma effect' mean that it is difficult to assess or quantify its contribution a process system.

Complex phenomena occur due to the interaction between the plasma, the liquid electrolyte and gas phases within the reactor. Collectively these combined benefits, i.e. the 'plasma effect', have been demonstrated to catalyse various reactions in other applications such as gas reformation, where highly reactive species such as free radicals are formed which accelerate chemical reactions. Similarly, the generation of free electrons within a plasma arc (Delgado, et al., 2019), due to the ionisation of the plasma gas, will provide highly reactive electrons to the system and electrolyte solution which have been proposed in the literature to also accelerate reactions and consequently hydrogen formation within the cell. Importantly, if pure (non-plasma effect) thermodynamics prevails the output should be 11g $H_{2\,(g)}$/kWh compared to 64 for methanol based on the thermal equilibrium models developed using the Metso HSC Chemistry simulation software. In the modelled pure water case (No 3) Tetronics only projected to achieve 3 kg/hr H_2 (on the as modelled basis) with 2-3 lph of water quench to keep the resulting temperatures down below autoignition.

Referencing Figure 4.1 and Phase 2, the reasons why the process didn't work as intended were primarily due to the difficulty or fragility of the LaB_6 tips to work within the plasma in the developed environment. Also, the susceptibility of the adjacent nested anode arrangement to damage due to plasma attachment and elements of the structure not being electrically isolated or cooled without feed and quench water flows. In summary the design didn't fully anticipate the transient operational requirements for establishment of the process. Overall, the process of managing and attempting to resolve this situation consumed a lot of time and resources. In conclusion the fragility of the new electrodes and the complexity of the design resulted in a move to Phase 3 and the application of Tetronics' conventional 38 mm transferred torches, Figure 4.1.

Phase 3 saw not only the move to transferred plasma torches, but also the independent dosing of feed and quench water into the cell and a focus on improving the operation of a single plasmolysis cell. This was a fundamental step in reaching a baseline for achieving the simultaneous operation of six cells. Central to the success of the process was the ability to sustain plasma whilst admitting water into the cell and therefore arc. Overall, power levels were pushed up at a unit cell level to the intended design threshold of 50 kW. However, to achieve this 12 off power supplies were utilised in parallel to give a higher current. This was required as the voltages developed by the process were less than expected, which were defined from the literature and the previous Phase 1 prototype work. This occurrence is interpreted as indicating a sub-optimal level of interaction between the plasma and spray. Factors that contribute to the arc voltage are working chemistry, temperature, pressure and arc length. In addition to this the cell engineering was revised, with the use of reconfigured PEEK and Macor insulators, with complementing assembly care points to improve thermal contact and minimise electrical shorts following the increase in power input. Plasma torch maintenance and assembly was optimised and controlled for the application, which allowed for hours of reliable continuous plasma operation as opposed to minutes. The quadrupole sampling line and spectrometer was configured to deliver 'clean' spectra, i.e. not contaminated excessively with water and a high background for the intentionally admitted argon gas, which essentially meant that the data are a true reflection of the cell's chemistry and the hydrogen response we are trying to achieve. During the implementation of this configuration the cell was modelled using Computational Fluid Dynamics (CFD), Figure 4.3.

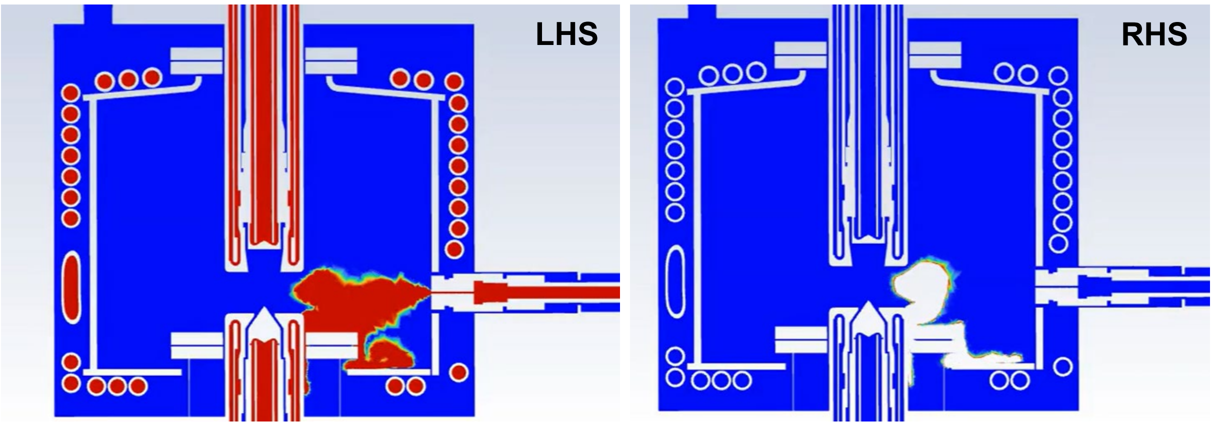

Figure 4.3: CFD output for a plasma operating at 20 kW (LHS - liquid water, RHS – water vapour)

The CFD indicates that the water flow gets to the periphery of the plasma but doesn't penetrate through it and vapour is formed only on the side of the water admittance. The corresponding temperature drop is shown in Figure 4.4. On first inspection it could be interpreted as plasma deflection but in fact it is more representative of the cell being asymmetrically cooled due to the admittance and phase transformation of the water.

Figure 4.4: CFD output of temperature distribution of a single plasma cell operating at 20 kW

4.2 Results of Demonstration Study

To improve the interaction of the plasma and water, and in addition to specific energy input increases, a range of quench and feedstock solutions were used with different configurations, which has allowed the correct water admittance rates to be achieved for a given power input, i.e. specific energy input is correct. Overall, there appears to be a power threshold for hydrogen production, but the hydrogen responses beyond this does not increase in-line with power addition as previously observed in Phase 1. Attempts were made to determine if hydrogen was being produced in the cell, at higher concentration, but back reacting once it leaves the plasma environment. An optical spectrometer was deployed for this purpose and spectra were acquired in a dry cell which confirmed the chemistry of the plasma, but unfortunately the signal was obscured due to the cell structure and admittance of quench water.

Referencing the ideal theoretical Faradic electrolysis performance the process would be determined to be achieving 1.46/25.4*100 = 5.7% energy use efficiency. Base line thermodynamics also aligned with this, based on a mass balance of hydrogen in as feed water versus hydrogen out as gas which also tied in with the concentration profiles detected. In simplified terms, irrespective of how we examined the system, performance was lower than expected and had degraded from Phase 1. The next stage of the evaluation was to determine where the energy was going; if it was being admitted but not being used to overcome the heat of reaction to produce hydrogen, i.e. something should be getting hot.

A standard heat loss calculation was used to calculate the average heat losses to the cell's water-cooled system thermal management system, as monitored at the manifolds. The cell cooling system includes the anode and cathode nozzles and electrodes and the cooling coils and flanges on the cell body. The cooling system also includes the heat exchangers used to remove the sensible heat of the spent quench liquid and gas outlet streams. In summary the cell was designed and configured for thermal audit and the results are presented in Table 5:

Table 5: Plasmolysis Cell Thermal Losses at 50 kW

	Heat Losses (kW)	Distribution of Loss (%)
Anode Electrode	- 0.86	9.13
Anode Nozzle	- 1.07	11.36
Cell	- 6.88	73.04
Cathode Electrode	- 0.23	2.44
Cathode Nozzle	- 0.38	4.03
Manifold	-	-
Total	**- 9.42**	**100**

In summary, and relative to a power input of 40 kW, the cell structure is determined to be 81% energy efficient. Which is lower than intended but reflects the late addition of larger than required water-cooled plasma torches to provide stable plasma. Of the 50 kW of plasma power admitted, through calculation it is determined that only 6.6 kW of power went into the process of producing hydrogen based on the composition and gas flow determined at the cells' exhaust. This means, of the net power available (50-9.42 = 40.58 kW), only 16% of it when into producing hydrogen and circa 34 kW is unaccounted for. This is best illustrated reference the complementing cell Sankey diagram, Figure 4.5.

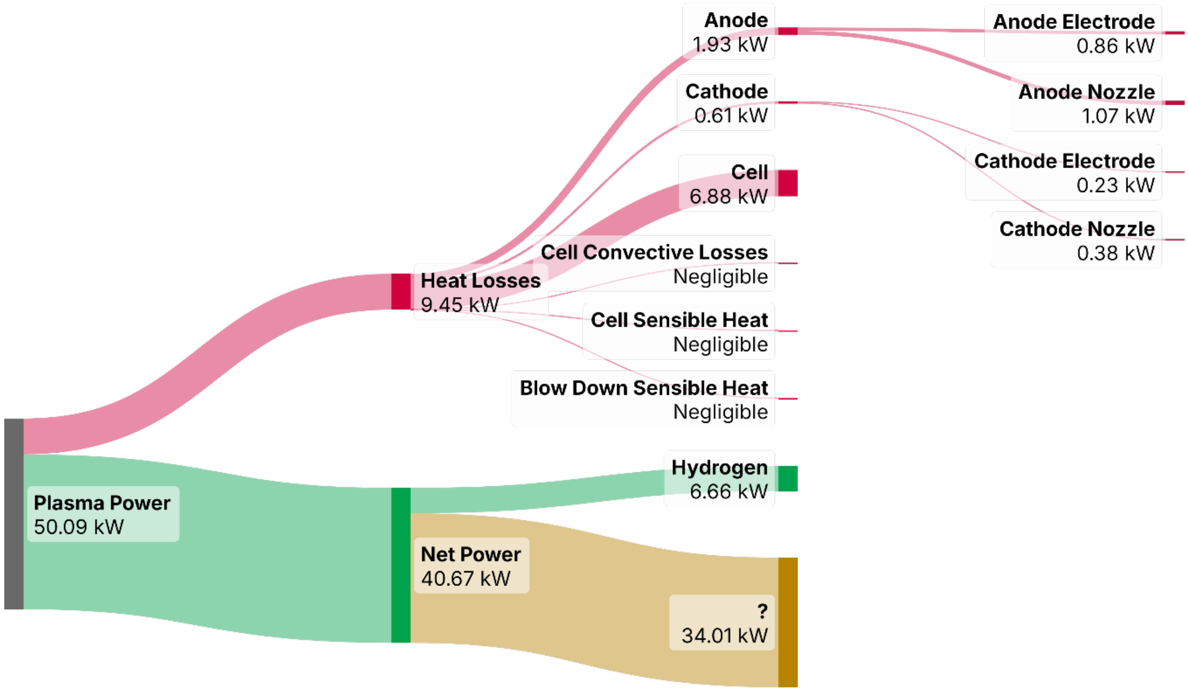

Figure 4.5: Cell heat balance Sankey diagram

Although the technology demonstration was able to produce hydrogen, the efficiency was significantly below the values Tetronics aspired to achieve. This could be because a heat sink wasn't accounted for within Tetronics' thermal audit, but nothing got excessively hot, or that the hydrogen was being produced but was recombining after the cell before the Hiden gas analyser determined the product stream composition. This however is unlikely as the reaction would be exothermic, and a significant amount of energy would be liberated somewhere within the system. There is also a possibility that the sampling protocol resulted in the analysed gas stream differing from the bulk stream, so not representative of the bulk composition. Again, this is unlikely as the sampling and analysis system was calibrated, in its entirety using a certified argon hydrogen calibration gas.

This recombination occurrence was allowed for in the design and the steep thermal profile of the plasma arc and the use of a water quench was meant to minimise the extend of any back reactions and facilitate safety. Other establishments have cited rapid gas cooling rates as key to the harvesting of hydrogen from plasma facility water thermolysis (Boudesocque, Vandensteendam, Lafon, Girold, & Baronnet, 2006). The CFD studies conducted indicate that the water spray did reach the periphery of the plasma arc asymmetrically, but didn't penetrate it, only generating water vapour locally which probably inhibited subsequent heat transfer. This would also suggest that the localised specific energy input to the feed water was below the threshold it should be at, and a larger number of water feedstock sprays should have been employed.

Positively, the cell did operate successfully at 3 barg with plasma and the determined oxygen concentration of the product streams were low, as per Phase 1, so safety concerns weren't realised but provisioned for irrespectively. Side arcing problems were minimised, and operating power densities were increased, but unfortunately they didn't improve productivity. Figure 4.6 illustrates this because as power increases the generation rate of hydrogen remains the same, but the efficiencies drop (based on both gross and net power input), with the difference reflecting the magnitude of the identified losses. Figure 4.7 presents data from the same operational period on a time basis. These data show that power, voltage and arc gap react together, but hydrogen generation rates aren't impacted by them, and they diverge from the thermal losses which climb at a much lower rate. Furthermore, the hydrogen production doesn't appear to trend with water admittance rates which would suggest limited plasma to water interactions.

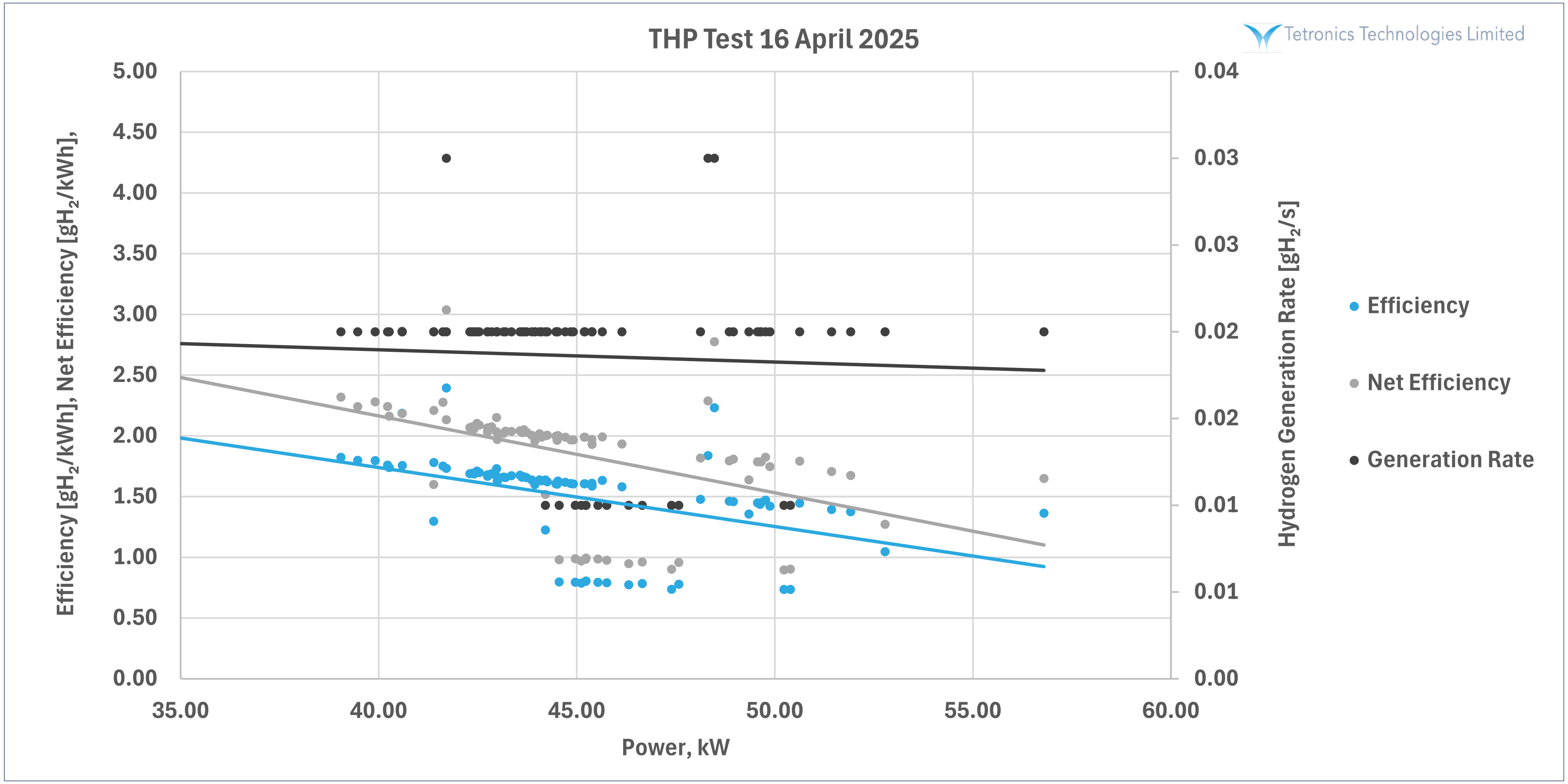

Figure 4.6: THP Hydrogen generation rate and efficiency versus input plasma power

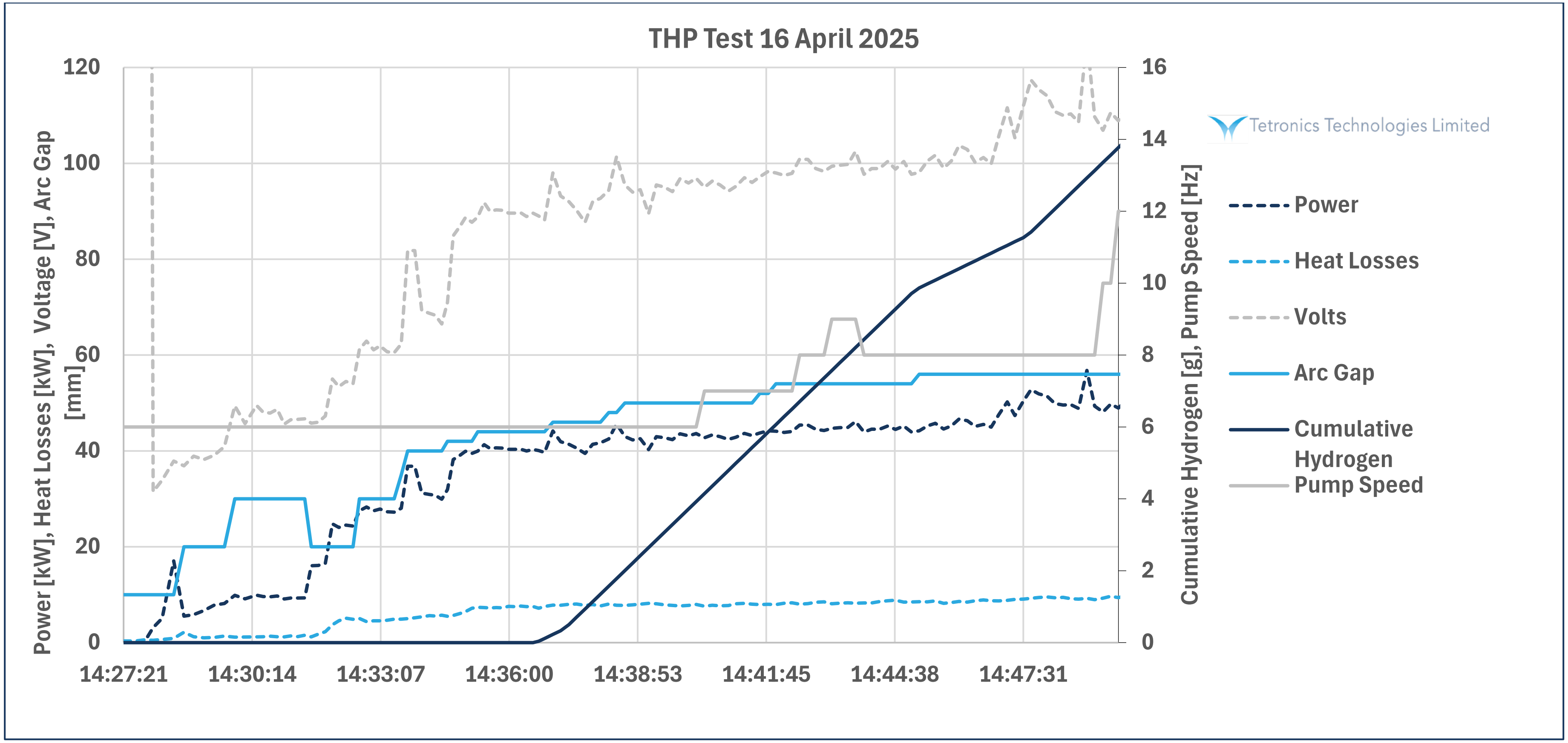

Figure 4.7: THP Plasma characteristics, water admittance and hydrogen production versus time

Experimentation has identified some gaps in the data recorded by the SCADA historian and the Hiden gas analyser and therefore some gaps in the data analysis.

The most significant gaps in the data acquisition were the lack of direct measurement of the argon flowrate achieved and of the product gas flow rate derived from the single cell operation. Equipment was procured and installed in the latter case but failed to function because of PLC compatibility issues. The inability to utilise a measured value for the argon flowrate meant that it was based on operator setpoints resulting in a reduced data confidence level. Furthermore, the gas composition determined by the Hiden QGA omitted the NO_x volume fraction in the output gas stream. Therefore, it is not known what fraction it made up in the output gas stream. NOx generation could make up part of the power that could not be accounted for as part of the thermal audit summarised in the Sankey diagram in Figure 4.5. NO_x was included in the thermodynamic modelling performed during the design phase of the project; however it was expected to be only a small fraction total gas flow evolved because the cell essentially operates under reducing condition in immediate proximity to the plasma due to the presence of the hydrogen as a reducing agent. Even if NO_x made up a greater fraction than anticipated it is unlikely to account for the total unidentified power. This should be validated in a future experimentation by including it in the Hiden mass spectrometer for analysis. It is reported by the Greenhouse Gas Protocol (2024) that nitrous oxide (N_2O), a major component of NO_x, has a global warming potential relative to carbon dioxide of 273. Therefore an analysis of the NO_x volume fraction in the output gas stream could also be used to inform design modifications for the treatment of the product gas as the release of NO_x from plasmolysis could pose a significant challenge in its commercialisation.

Whilst calculating the heat losses a discrepancy was identified between the flow measurement devices on each of the cell components (cooling coils, cooled flanges and heat exchangers) and the total manifold measurement. This arises even though thorough checks were performed during cold commissioning. The difference between them could account for approximately 10 kW of losses and therefore could make up to one third of the unidentified power. For future experimentation the losses should be validated by recalibrating the flow devices on the cells and manifold and cross referencing their performance.

A gap in understanding remains for the balance of oxygen. The Hiden gas analyser results do not show enough oxygen when compared to the mass of hydrogen measured. The oxygen could be reacting with the surface of the cell however the materials of construction were selected such that they were tolerant to oxidation. Another potential route for oxygen to leave the system is its dissolution in the water drained out from the gas stream heat exchanger. This however is unlikely to account for the full balance as oxygen saturates water at approximately 8 mg/L at 30 °C. Across the test this could only account for milligrams of oxygen however the amount should be in the order of grams.

Reflecting on these data and analysis, moving forward it is proposed that the instrumentation for thermal auditing is comprehensively examined and modified or repaired to rectify the identified balance discrepancy. The flow transmitter(s) for determining the total product gas flow rate should be improved to ensure real time data are used. Also, and for completeness, the working routine of the Hiden QGA should be amended to include for NO_x in a bid to account for oxygen. The cell's geometric configuration should be amended to improve the localised coupling/induction of the water/hydrogen carrier feedstock and plasma, and the configuration of this system should maximise cooling rates to inhibit back reactions, i.e. optimal incident and expulsion rates. This optimum configuration should be confirmed using a CFD study, before releasing the design for physical manufacture. Analysis should allow for the composition of the gases to be assessed immediately within the cell using the QGA but also the optical spectrometer.

5 Project Metrics

As can be seen from the technical sections of this report, whilst TTL was able to generate some hydrogen, the levels produced were significantly lower than anticipated. Within the timeframe given and with the low levels produced, TTL was unable to progress to the downstream elements of the system such as compression and purification of the hydrogen product.

The project aimed to raise the TRL from 6 to 7; however, given the challenges faced, the technology remains at TRL 6. Consequently, it was not possible to report certain key metrics used to compare similar technologies, as these would typically include major unit operations such as compression and pressure swing adsorption.

A purified hydrogen product was not separated from the output gas stream, which was instead combusted using a locally compliant off-gas system. Therefore, it was not possible to report the hydrogen product's purity, volume, or pressure. Similarly, because a full demonstration of the process was not conducted, it was not possible to calculate metrics such as feedstock usage, potential production capacity, round-trip efficiency, total process carbon emissions, or the durability/lifetime of the production technology (in hours).

The levelized cost of hydrogen remains the same as at the beginning of the project.

A separated trial report provides details for the following metrics.

- Efficiency of production technology
- Thermal and power demand
- Energy associated with production (kWh/kg H2)

6 Project Management

6.1 Structure and Scheduling of Project

The project was structured into 5 main work package phases which are described below. These phases align with the TTL New Product Introduction Process (NPI) which allows for a gated and phased review process to be undertaken throughout the project lifecycle.

WP01 – Design Phase

This Work Package formulates Phases 1-4 within TTL's New Product Introduction (NPI), phased and gated process and comprised of Concept Design, Preliminary Design, Detailed Design and Final Design elements. There were formal design reviews at the end of Preliminary Design (PDR), Detailed Design (DDR) and Final Design (FDR) where a review panel consisting of members of TTL Leadership Team assessed the design progress at each of these stages and gave authorisation for the design to move onto the subsequent phases. Key Deliverables at each stage included the following

- Concept Design
  - Process Model
  - Plant Basis of Design
  - Concept Plan Layout
- Preliminary Design
  - 2D Thermal Model
  - Plant Requirement Document
  - Equipment Requirement Documents
- Detailed Design
  - HAZOP Study
  - General Arrangement Drawings
  - Piping and Instrumentation Diagrams
- Final Design
  - Bills of Material
  - Manufacturing Drawings

WP02 – Manufacturing and Assembly

This WP contains Phase 5 of TTL's NPI Process and included both the Long Lead Items Procurement and the General Procurement of the equipment required for the assembly of the Tetronics Hydrogen Plasmolysis (THP) 300Kw Cell. The key output from this phase was for all necessary orders to be placed. Deliverables included

- Supplier Mobilisation
- Supplier Design Review
- Supplier Delivery
- Operations and Maintenance Manual

- Installation Plan
- Commissioning Procedures

WP03 – Installation and Commissioning

This WP covered Phases 6-8 of TTL's NPI Process and included the installation of the THP Plant followed by Cold Commissioning of the Plant where the individual equipment that form part of the THP Cell and the supporting equipment were individually tested, calibrated, and set up accordingly. This then led onto Hot Commissioning of the plant where the Plant was turned on and ran for a period to ensure that all the equipment that made up the Plant were integrated and functioning together as a complete system. Deliverables included

- Cold Commissioning Certificate
- Hot Commissioning Certificate

WP04 – Demo Plant Performance and Validation Testing

This WP covered Phase 9 of TTL's NPI Process and included periods of Plant Performance Testing designed to validate that the THP Plant could deliver the expected requirements as well as a period of Plant Durability Testing designed to ensure that the THP plant could produce Hydrogen reliably without process or equipment failure. The Hydrogen Plasmolysis process and devices were characterised at the expected scale of hydrogen production as part of these tests. The key deliverable for this WP included

- Trials Procedures
- Safe Systems of Work (SSOWs) and Risk Assessments (RA)
- Performance and Durability Test Data

WP05 – Analysis and Reporting

This WP included planning, scheduling, and monitoring. Progress were assessed using Project Tracking and Reporting. Regular risk reviews and financial reporting were conducted. TTL delivered this WP in line with the NPI Process and its own internal Project Management Quality Procedure.

This Work Package also analysed all the data gathered in WP04 for both the Performance Testing and the Durability Testing in order to produce the final report. The key deliverable for this WP is

- Final Report

6.2 Recruitment Activities

During the course of the project, TTL recruited a number of new staff specifically to aid with the delivery of the project and those new roles are listed below:

- Mechanical Fitter – start date Jan 2024

- Mechanical Fitter – start date Mar 2024
- Mechanical Fitter – start date May 2024
- Process Engineer – start date May 2024
- Mechanical Engineer – start date Sep 2024
- Senior Project Manager – start date Sep 2024

6.3 Key Risks, Mitigations and Issues

A Risk Register was raised and reviewed at the beginning of the project. As the project phases developed, a couple of the above risks became issues that TTL did attempt to mitigate as much as possible to lessen their impact on the delivery of the project.

During the manufacturing phase, the key issues that TTL faced were reported to DESNZ at the time as follows:

Work Package	Title	Issue description	Date reported	Expected Resolution Date
WP22	Delay to compressor delivery	Fluitron have indicated a 2-3 month delay to the delivery. Contracted ready to ship date was 24th April 2024. Current proposed date is end of October 2024.	21/01/2024	30/10/2024
WP22	Delay to PSA delivery	IVYS reported this month that they have 3rd party certification issues causing overall delay to the delivery. The system is due to arrive in December 2024.	16/07/2024	18/12/2024
WP07	Torch Nozzle Components	NSK Precision Engineering Ltd who were supplying key torch components has gone into liquidation. Currently gone out to Supply Chain to seek alternative suppliers – awaiting quotes back this week.	12/07/2024	11/10/2024

For the torch nozzle component company that went into liquidation, TTL mitigated this issue by partially redesigning an element of the torch such that another manufacturer could be identified to supply the components. Whilst these components were awaited, TTL continued to manufacture the torch to avoid any knock-on effect to the schedule.

For both the Compressor and PSA suppliers, TTL embarked on regular progress meetings with the senior management of both organisations to try and mitigate the delivery delay as much as possible. Financial penalties were also applied to both organisations in terms of liquidated damages as a result of their late delivery. Again, to try and mitigate the overall effect on the schedule, TTL built, commissioned and tested the system in parallel and out of sequence to enable the project to continue whilst these components were still being manufactured.

Clearly the number one technical risk of being unable to generate the hydrogen at the required rate became an issue in the Hot Commissioning and Testing phase of the project and has been described already within this report.

7 Secondary Project Benefits

7.1 Dissemination Activities Undertaken Including Media Coverage

- TTL exhibited at the Reset Connect Event in London in late June 2024.
- TTL were part of the Climate Innovation Forum in late June 2024
- TTL presented at H2 Tech Expo in Hamburg on 23rd - 24th Oct 2024.

7.2 IP Generated from Project

The Intellectual Property (IP) generated takes two primary forms, un-recorded rights that are protected through copyright and also know-how on how to design, manufacture, assemble and operates the cells safely producing plasma at 3 barg and splitting water to product hydrogen. Beyond this there are register rights primarily in the form of patents, the reason for two patents reflected the evolution of the design moving from BEIS to DESNZ, i.e. electrical versus fluid communication of the thermolysis and electrolysis elements of the process. The first patent is GB2207337.3 which was filed in 2022 and has been published and favourably examined (yet to be granted). The patent is filed in the UK, China, USA and Taiwan using the Patent Cooperation Treaty application process. The second plasmolysis patent was filed in July 2024 and is GB2410806. This patent is less mature but has been examined nationally, but is yet to be published. It is filed in the UK, China and USA only.

7.3 Number of jobs Created and Improving Skills/Experience in Sector

See Section 6.2

7.4 New Partnerships Formed from Project (UK and International)

No new partnerships have been formed during the course of the project.

7.5 Supply Chain Development

New suppliers have been engaged and contracted with although some of these have caused a number of issues with delivery delays during the project. TTL existing supply chain also provided equipment and componentry during the project and reinforced their reputations as known and approved suppliers.

8 Commercialisation Plans

8.1 Route to Market Assessment

Tetronics' Hydrogen Plasmolysis (THP) novel approach offers a potentially more efficient and flexible alternative to traditional green hydrogen production methods. THP compares favourably with current best in class electrolysers, offering:

- Higher efficiency enabling H2 cost of circa $1-2/kg with optimisation and scale up.
- Feedstock flexibility – including saltwater, ammonia and methanol.
- Extended operational life (99% performance after 30+ years).
- Tolerance to power outages - rapid start stop and system turn down.

8.1.1 Proposed Routes to Market

The proposed routes to market for Tetronics THP technology involve targeting industries and sectors that require hydrogen for various applications. This includes the chemical industry, refineries, transportation, and energy storage. The technology can be marketed as a flexible and efficient alternative to traditional hydrogen production methods.

Optimum first use clients to be targeted include:

- Offtaker who is a large/medium energy user and therefore not solely dependent on the THP hydrogen.
- Facility is already constructed so project can “bolt-on”, hence no need to align with future projects/upgrades.
- They have systems in place for handling/processing of pressurised gases.
- Sector appetite for hydrogen – hence not a novel application meaning less obstructions/approvals.
- They have public UK hydrogen or carbon capture projects (such as Hydrogen Allocation Rounds, Net Zero Hydrogen Fund or in public domain).

- Be based in or near Industrial Clusters (such as HyNet North West, Teeside, Humber, Solent South-East, South Wales Industrial Cluster, Acorn Scotland).
- They have access to their own Green energy.

8.1.2 Commercial Scale Development Considerations

When considering commercial scale development, several factors need to be taken into account:

- Market demand currently in the MW scale but expected to grow to 100MW plus.
- The scalability of the technology whilst minimizing cost and operational availability.
- Economic feasibility and return on investment.
- The integration of the technology into existing industrial processes.
- Supply chain implications for scaling equipment.

This has led to a modular architecture that allows production units to be sized and grow in capacity as the market develops. Starting with 1MW and scaling to 10MW or larger through multiple modules.

Scaling up the equipment for commercial production will require a robust supply chain to ensure the availability of critical components. This includes establishing a high-quality THP cells production facility, and strategic partnerships with multiple power supply companies, and other essential equipment. Tetronics already has relationships with multiple potential suppliers who can operate on the scale and volume targeted, through its current trading activities. A new THP manufacturing facility will be developed an operated by Tetronics to satisfy demand as it grows. Initial demand can be satisfied from existing infrastructure.

8.1.3 Expected Lifetime of Plasma Cells and Plant Equipment

The expected lifetimes of THP cells and other plant equipment are crucial for determining the overall cost-effectiveness of the technology. Plasma technology typically has a lifespan of 30+ years, depending on the operating conditions and maintenance practices and compares very favourably with the best-in-class electrolyser alternatives, providing a significant cost of ownership advantage over the life of the plant.

8.1.4 Maintenance Requirements for Plasmolysis

Given that plasmolysis is a novel technology for hydrogen production, it is essential to establish a comprehensive maintenance plan. This includes regular inspections, cleaning, and replacement of worn-out components. Preventive maintenance practices will help to ensure the reliability and efficiency of the system, minimizing downtime and operational disruptions.

8.1.5 Electricity Sourcing Strategies

The electricity required to power the plasma torches can be sourced from the grid or directly connected to renewable energy systems. If connected to a renewable system, such as solar or wind, the production can potentially ramp up and down in line with generation rates. This flexibility can help optimize energy usage and reduce operational costs. Alternatively, using grid electricity provides a stable and reliable power source but may involve higher energy costs.

8.1.6 Flexibility of Production with Renewable Energy

Connecting the plasma torches to a renewable energy system offers the advantage of adjusting production rates based on the availability of renewable energy. This flexibility can help align hydrogen production with periods of high renewable energy generation, maximizing the use of clean energy and reducing carbon emissions. The THP unit has not been tested with a renewable energy source as part of this project but as the plasma torches are powered from electricity, TTL are confident that direct connection to a renewable energy system would not be an issue.

8.1.7 Rationale for 1MW and 10MW Unit Sizes

The size assumptions for 1MW and 10MW scale units are based on the anticipated demand for hydrogen and the scalability of the technology. These unit sizes provide a balance between production capacity and operational efficiency, allowing for gradual scaling up as market demand increases. Additionally, the technology offers flexibility to build commercial scale systems of different sizes to meet specific customer requirements.

8.1.8 Competitive Positioning against Electrolysis

Tetronics THP technology can be marketed against electrolysis by highlighting its advantages, such as:

- Higher efficiency enabling H2 cost of circa $1-2/kg with optimisation and scale up.
- Feedstock flexibility – including saltwater, ammonia and methanol.
- Extended operational life (99% performance after 30+ years).
- Tolerance to power outages – rapid start stop and system turn down.

The technology's potential for integration with renewable energy sources further strengthen its competitive positioning.

8.1.9 Qualitative capex/opex Comparison with Electrolysis

In terms of capital expenditure (capex) and operational expenditure (opex), Tetronics THP technology can offer cost advantages over electrolysis. The lower energy requirements and potential for using renewable energy can reduce operational costs. Additionally, the scalability and modularity of the technology can help optimize capital investments and reduce the overall cost of hydrogen production.

8.1.10 Hydrogen Offtake Options

The hydrogen produced using Tetronics THP technology can be off taken through various methods, including tube trailers and pipeline networks. Tube trailers offer flexibility for transporting hydrogen to different locations, while pipeline networks provide a continuous and reliable supply to end-users. The choice of offtake method will depend on the specific requirements of the customers and the infrastructure available. Early market dialogue with potential first customers is dominated by clients wishing to consume the hydrogen onsite for their own decarbonisation processes. This would require some compression at local storage to buffer the gas flow from the THP unit to the hydrogen consumption point.

8.2 Access to Revenue Support Mechanisms

Once the next phase of THP scale-up is achieved, it will be eligible for future Hydrogen Production Business Model (HPBM). As a result of the modelling and testing that has been undertaken so far, the THP technology will be compliant with UK Low Carbon Hydrogen Standard (LCHS), provided that a suitably green electricity source is identifed and connected to the system.

8.3 Outcome(s) of Conversations with Prospective End Users

See details below in 8.4.

8.4 Information Provided by DESNZ Acceleration Support

TTL received support from the NZIP Acceleration Support Programme within the period of April 2022 to March 2025 in the form of Minimal Financial Assistance (MFA) which allowed the following activities to take place.

- NZIP Acceleration Support Programme engaged.
  - 1st Phase - Report highlighting TTL target audience.
  - 2nd Phase - Shortlist 6 to 12 companies that are a good fit as a potential partner for the first operational demonstrator.
- TTL then engaged Mott McDonald (MM) to provide a shortlist of six attractive potential partners for TTL's first operational demonstration plant (1-5MW). A kick off meeting was held in May 2024 and workshop was held in June 2024.
- Two companies were identified for exploratory talks with pitch packs prepared.
- Exploratory talks with one organisation still continuing as the project progressed.
- A further two potential clients have expressed interest in collocating the technology with existing or planned wind turbines. One of those clients will utilise the H2 to decarbonize an existing industrial process in the oil and gas production sector, the other proposes to use spare wind power to make transport grade H2 for the local authorities fleet of H2 powered vehicles.

9 Conclusions and Next Steps

9.1 Was the Project Able to Achieve Its Objectives

The overarching aim of the project was to scale up the Prototype by incorporating the lessons learned from that system to design and build an end-to-end plant which can produce pure hydrogen at a rate of 7 kg/h with a plasma power input of up to 300 kW. The key output from the project was the valuable lessons learned during each phase which are detailed below. The most important lesson was that TTL, through its extensive commissioning and testing process, which conducted alongside its complex CFD modeling, was able to identify the root cause of the reactions not occurring as initially expected. Furthermore, the findings showed that with specific modifications to the current design, the target levels and efficiency of hydrogen production can still be achieved.

9.2 Lessons Learned

9.2.1 Project Management Lessons Learned

The key project management lesson learned was undoubtedly in allowing the technical solution to move away from the prototype design to DESNZ#1 configuration in an attempt to improve production efficiency which clearly introduced a number of other unknown factors that caused operational issues and delays.

Time was spent trying to find materials for tips that would allow DESNZ#1 configuration to work and this put additional pressure on what was already a tight schedule.

The team should have focussed more on building on the success of the prototype and should have switched to the DESNZ#2 configuration sooner such that plasma stability with known and proven torch technology would then allow the time in the schedule to optimise this configuration.

9.2.2 Supply Chain Lessons Learned

The three main issues described in Section 6.3 were all related to supply chain and provide a good illustration of the supply chain lesson learned on the project. The delays associated with the delivery of the compressor and PSA as well as the torch nozzle company going into liquidation demonstrates the pitfalls of establishing a new supply chain for equipment and components that have never been procured before. Clearly the companies involved did not operate and deliver in the manner they were contracted to and they were all organisations that were new to TTL who typically use known, good and approved suppliers who have been connected to the business throughout a number of projects.

9.2.3 Technical Lessons Learned

The most valuable lesson was that TTL, through its extensive commissioning and testing process - conducted alongside its complex CFD modeling - was able to identify the root cause of the reactions not occurring as initially expected. This was primarily due to the feedstock delivery mechanism.

A proposed redesign of the feestock delivery mechanism should enable higher production rates, and this has been validated through CFD modelling. The proposed modifications could be retrofitted to the cells built for this project with some minimal design changes, allowing the target levels and efficiency of hydrogen production to be achieved.

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