Department for
Business, Energy
& Industrial Strategy

Translational Energy Research Centre

Project Summary Report

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Executive Summary

Overview

The Translational Energy Research Centre (TERC) provides the infrastructure and expertise for research, development and innovation (RD&I) in sustainable energy technologies, with the aim to boost cooperation between research institutes as well as expediting the commercialisation and use of these new technologies by commercial and industrial businesses, including suppliers.

The project has been part-funded by the 2018 'Call of CCUS Innovation' fund, via a £7m investment in 4 bespoke pilot scale research facilities totalling £4.7m and the remaining funds contributing toward the creation and operation of a £21m research facility. The 4 items of bespoke research equipment include:

- Sustainable Aviation Fuels Production Facility
- Molten Carbonate Fuel Cell
- Shock Tube Chemical Kinetics Test Facility
- High Pressure High Temperature Heat Exchanger Test Bed (HEX Facility)

This document provides a post-project analysis, specifically of the project management aspects of each of the 4 pieces of project equipment. The document outlines factual aspects of each project, including the original project intention, procurement activities, legal matters, project budgets and programmes. The document also provides qualitative analysis of project history and lessons learned.

Project Summary

Molten Carbonate Fuel Cell:

- The Molten Carbonate Fuel Cell (MCFC) combines CO2 capture with electricity cogeneration. The unit was intended to be interfaced with all combustion plants (through the flue gas manifold system) for post-combustion capture as well as with the ACP and MCP for treating of CO2-enriched gases generated by the MCFC, and ultimately with the CCU plant(s).
- The successful bidder, Fuel Cell Energy (FCE), proposed a 30kW MCFC demonstration module based on the design and sizing of their own internal R&D pilot facilities. The 30kW scale meets the criteria of the ITT and fits well with the TERC infrastructure and other pilot scale facilities.
- Following the first tender, which returned 2 inadequate bids, the project team sought to revise the technical specification of the tender and to inform all market leaders of the technology of the tender via advertisement, with a view to maximising the possibility of positive outcome. This resulted in the submission of a bid by the ultimate successful bidder; Fuel Cell Energy (FCE).
- However, due the proprietary nature of the technology and FEC's concerns regarding IP and the University's intended use of the research apparatus the contract required significant amendment, and contract negotiation took 9 months to complete.
- At the time of writing, the main module of the MCFC was delivered and in the process of installation. However, the project team estimates the final balance could be circa 400% above the original conceptual market research.
- The following key lessons learnt were identified:

- The UoS project recognises that whilst a significant volume of market consultation was conducted prior to the release of the ITT, the project team significantly underestimated the cost of the MCFC system.
- The tender period for the first tender was far too short for a project of this magnitude.
- It is recognised that the significant increase in estimated budget will in part be due to changes in the supply chain as a result of factors such as Brexit and Covid-19 that may have contributed to the extreme variation.
- The project team recognises that contract negotiation periods for complex technologies needs to be considered when scheduling projects at the concept phase as in this instance this phase took more than 9 months.

Shocktube, Chemical Kinetics Test Facility:

- To complement the research conducted in the High Temperature High Pressure Heat Exchanger Test Bed (HEX rig), TERC will also include a high pressure shock tube with analytical ports for fuels chemical kinetics research.
- The successful bidder, Heblac Technology Gmbh, proposed a stainless steel shock tube with world-leading capabilities including: an inner diameter of 101.6 mm, a total length of 10.7m, a working pressure of 500 bar @ 125 °c. Combined with an award-winning SolsTiS Laser and a next generation continuous-wave Ti:Sapphire laser supplied by M Squared Technologies.
- WSP Ltd, a engineering design consultancy company, were employed to produce the full engineering design for the system to inform the tender specification.
- However, during tender evaluation, it was also concluded that none of the bidders provided a bid that met all the technical requirements. However, during a technical specification development WSP identified a suitable vendor, which ultimately resulted in Heblac Technology Gmbh being awarded the contract.
- The following key lessons learnt were identified:
  - Even when applying maximum due diligence to the specification development, open tender procurement exercises remain a challenge. Project teams should consider this the conceptual phase of the project. Whilst the objective of the project as a whole was to drive innovation, procuring technologies in this way can be a challenge, as companies would prefer shared risk design collaboration projects as opposed to direct turnkey design and build contracts. Often this is not considered an option due to the tight programme constraints of grant funding deadlines, however project teams should evaluate other procurement options at the concept phase.
  - The laser diagnostic tender and procurement process was a far smoother experience with this project due to elements of the design integration with the shock tube being resolved by WSP. Further highlighting the importance of obtaining external design support.

High Pressure high temperature Heat Exchanger (HEX) test bed:

- High pressure, high temperature Heat Exchanger (HEX) test bed for high-efficiency power conversion cycles R&D, focusing on supercritical CO_2 (sCO_2) for oxy-fired gas cycles but also with global applications in other power (e.g. nuclear) and industrial sectors

- The final High-Pressure Heat Exchanger test bed (also referred to as the HEX facility) which operates in the critical CO_2 range achieved all of the original design intent outlined in the original grant funding agreement.

- Following a similar approach to the tender specification as the shock tube facility, with the employment of an independent design consultant, the project was awarded to Helical Energy Ltd (Helical) with a contract to supply a turnkey High Temperature High Pressure Heat Exchanger Testbed (HEX).

- At the time of writing, the test bed had been delivered and the majority of the install works were complete, with a commissioning schedule within weeks.

- The following key lessons learnt were identified:
    - As identified with previous procurement exercises, the development of strong specification is essential. Therefore, the project team's decision to procure engineering design support to develop the tender specification is considered to be a key element for the success of this project.
    - Despite the efforts pre-tender to develop the design and an extensive period of design there were still a few oversights or elements of the specification that were not captured at the contract stage. This resulted in a circa 15% increase in the project budget. Fortunately the project team had sufficient funds to support this addition. However, it's clear that it is necessary to allow for a contingency even on complete design and build turnkey contracts.
    - Despite the principle contractor being held to milestones by contract, it became clear early within the project that the supplier had been extremely ambitious with the programme for a completely custom research rig. It is clear that it is the responsibility of the user/contracting party to take some responsibility for specifying realistic requirements in terms of cost, program and quality at the tender phase.

Sustainable Aviation Fuels Production Facility:

- The Sustainable Aviation Fuels Production Facility originally identified as the Methanation Plant was developed to focus on carbon dioxide utilisation as part of the full CCUS chain.
- Throughout the design process the technical scope of the project was refined and enhanced in order to maximise the flexibility and novelty of the pilot plant. The project team set the principal contractor 3 key objectives: 1. To produce 1-1.5 L/hr of aviation fuel base hydrocarbons. 2. To be flexible and modular as far as possible to accommodate future changes 3. There must be ancillary equipment for emergency shutdown to a safe state, regeneration of the catalysts, gas mixing, prevention of catalyst contamination, compression, heating and cooling of reactors and process sampling.
- Strata Technology Ltd (Strata) won the design and build contract to supply University of Sheffield (UoS) with a turnkey Sustainable Aviation Fuels Production Facility
- During tendering, despite the comprehensive research undertaken during the market consultation phase and several expressions of interest, only one company returned a formal bid.
- At the time of writing this document, Strata had advised the University that a significant increase in budget would be required to complete the project. The University is considering options including: 1. Continue the project with Strata Technology Ltd by increasing the budget and programme via formal contract. 2. Terminate the contract with Strata Technology following a period of asset and intellectual property acquisition. 3. To re-tender for the project for open formal tender.
- The following key lessons learnt were identified:
    - The project team concluded that the design, development and market assessment phase of technologies of this size and complexity warrants additional external specialist engineering and commercial support in the future.
    - The tender period was far too short for a project of this size.

  - The project team recognised that the ITT should have included a more detailed cost table, thereby requiring bidders to break down the budget proposal in more detail. In turn enabling the budget to evaluate more closely for accuracy and adequacy.
  - The proposed introduction of the RWGS reactor which was introduced at pre-award resulted in Strata naively not considering the time and budget required to introduce such a technology. The project recognises that in the future any change introduced post ITT issue may be a compliant practice but does introduce a significant technical risk.

Design milestones must be policed and adhered to rescue scope drift, regardless of any short term impacts to the programme.

Introduction

Background

The University of Sheffield (UoS), a member of the Russell Group of research-intensive universities, ranks in the top 10 of UK universities for research funding and is 75th in QS World University Rankings.

To help drive the type of collaborations between universities, businesses and the wider community that would generate real returns to the UK, in 2001 UoS established the Advanced Manufacturing Research Centre. This unique cluster of industry-focused manufacturing RD&I centres and supporting facilities has since become a model for collaborative research worldwide.

Energy was and continues to be a strategic priority of UoS, with a new Energy Institute launched in 2019. With continued investment, the aim is to capitalise on the leadership, expertise and facilities to provide an institutional framework for multidisciplinary collaboration in energy research and innovation.

PACT National Facilities, was founded in 2012 and was the UK centre for developing high efficiency, fossil fuel-based power generation and CO2 capture technologies that are reliable, environmentally acceptable and cost effective. It enables government, industry and university-led projects to conduct meaningful tests in an industrial setting, allowing results to be scaled confidently to commercial application, thus significantly shortening development times. PACT delivered a strong track record of projects, but a key part of the PACT strategy was to continue to expand CCUS research facilities in support of both academic research and higher TRL research better aligned with industry needs. The PACT site was considerably space constrained, hence the ambition to enhance and relocate the facilities was born. The Translational Energy Research Centre (TERC) would be become the replacement to PACT and would align with the grant call, specifically in response to:

- Industry-driven need to expand the research facilities to include CO2 utilisation, Hydrogen CCS, BECCS and Waste to Energy CCS.
- Opportunities to exploit research areas which have significant growth potential - if they have access to larger scale facilities.
- Industry and academic demand for enhanced capacity, flexibility, and increased “collaboration space” – especially for SMEs.
- The risk of any individual research area rapidly growing or shrinking, expanding PACT’s capabilities would support the long term sustainability of the centre.
- The need for a higher specification building with superior infrastructure, which would also be more in keeping with UK national facility status.

The grant was successfully awarded in February 2019. The wider project included the construction of an 1800sqm facility, 4000sqm external research area and specialist mechanical and electrical infrastructure package to support a wide range of technologies. The project design and build project commenced immediately and concluded with the completion of the specialist infrastructure package in December 2021. This grant part-funded the construction of the building with the majority of the funding award for the procurement of 4 pieces of specialist pilot-scale research equipment, including:

- Sustainable Aviation Fuels Production Facility
- Molten Carbonate Fuel Cell
- Shock Tube Chemical Kinetics Test Facility
- High Pressure High Temperature Heat Exchanger Test Bed (HEX Facility)

The TERC state-of-the-art facilities provide all the realistic operating conditions of heavy industry or power plants, as well as a highly skilled team and the infrastructure to install and evaluate the most promising carbon capture technologies for scale-up and future commercial deployment. Novel bench- and pilot-scale processes will be evaluated over a range of operating conditions for efficiency, environmental performance and economic viability.

Report Scope

This report discusses the BEIS-funded Translational Energy Research Centre (PACT 2) project from a project management perspective. Specifically, this report discusses in detail each individual item of research equipment funded under the BEIS grant only. It should be noted that the Translational Energy Research Centre Project consists of a wide range of pilot-scale research facilities, funded in multiple ways.

The report considers the full life cycle of each piece of funded equipment, beginning with the original project design intention as a marker for the technical and quality scope, through to the final design position. Thereby providing a measure of change encountered throughout the project lifecycle. As well as justification for changes and acknowledgement of failure where appropriate

Furthermore, the report provides all the key equipment project metrics, including the original budget versus actual following realisation of each project, as well as details of the project milestones, forecasts and so on. Moreover, the report also provides a brief history of events, with the view that this will convey to the reader the challenges associated with this project, allowing the reader to identify parallels with similar projects.

Finally, following consultation with the wider project team, this report details the lessons learned from a financial, commercial and project management perspective, with the view to assist the reader and to inform and inspire good decision making principles in future projects of this kind. To conclude each section, this report openly evaluates the success of each project at the time of the report, based on the 3 pillars of project management: Cost, Programme and Quality.

Sustainable Aviation Fuels Production Facility

(Features a novel Fischer Tropsch (FT) reactor and Reverse Water Gas Shift (RWGS) reactors)

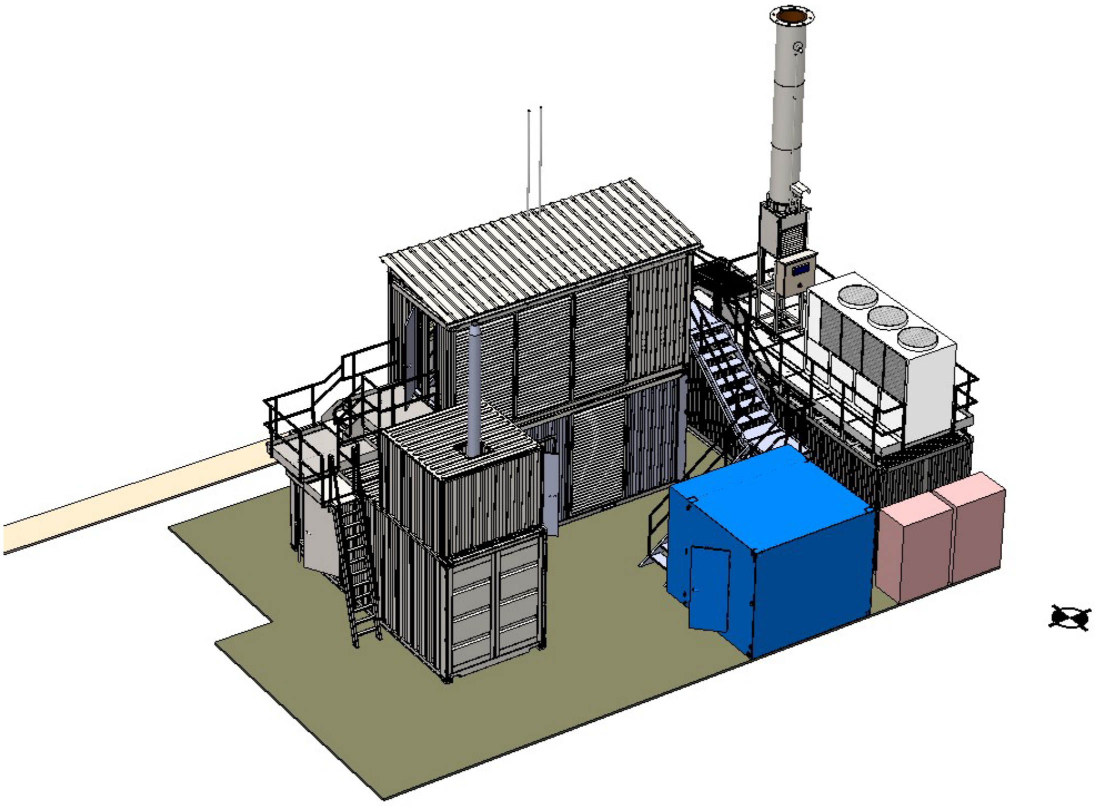
This section details all the key project metrics and provides a factual based narrative of the project's historical events and key lessons learned, with the aim of advising the reader of the challenges experienced in projects of this kind.

Original Project Design Intent

The Sustainable Aviation Fuels Production Facility originally identified as the Methanation Plant was developed to focus on carbon dioxide utilisation as part of the full CCUS chain. The original intention for the facility was based on Sabatier reaction of hydrogen and CO2 to produce SNG, reaction: $CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \;\; \Delta_r H_{298} = -165$ kJ/mol. The CO2 being supplied as a product gas (via an intermediate storage tank) from capture facilities ACP, MCFC and MCP and hydrogen generated from on-site electrolysers powered by renewable electricity or other CHP plants on site. In addition to real product gas, the facility was designed to be connected to the on-site GMF for supplying high purity cryogenic CO2 with an option for trace gas injection for synthetic gas operation in research on the impact of impurities on the process.

From the outset the facility would enable research on integrated power/industrial CCUS chain operations including dynamic operations as part of grid simulations. In addition to CCU application the technology would also provide a form of intermediate energy storage. Where storage and distribution of large quantities of hydrogen can be problematic, conversion to methane provides a general use, convenient fuel generated from biomass (primarily) and renewable electricity and, if combined with CO2 capture when utilised (e.g. through MCFCs), thereby creating a closed CO2 loop.

It was hoped that this R&D facility will be of interest to OEMs (e.g. Sunfire), gas grid operators, H2 and CO2 producers and the CCU industry.



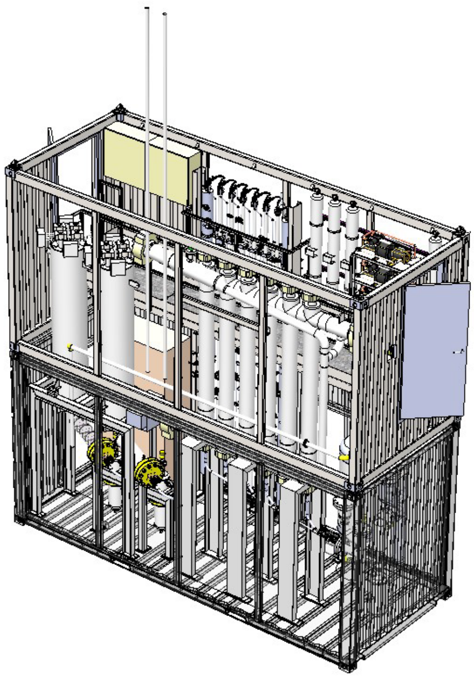


Figure 1: Example of design intent

Final Project Design Outcome

During the tender phase and throughout the design process the technical scope of the project was further refined and enhanced in order to maximise the flexibility and novelty of the pilot plant. The project team set the principal contractor 3 key objectives.

1. The plant was to produce 1-1.5 L/hr of base hydrocarbons which could then be upgraded for use as aviation fuel. To meet this requirement, three major unit operations in use were proposed. The first being a Reverse Water Gas Shift (RWGS) reactor in which Carbon Dioxide and Hydrogen will be reacted to produce Carbon Monoxide. The second being a Fischer-Tropsch (FT) reactor in which the Carbon Monoxide and Hydrogen mixture (Syngas) will be reacted to produce liquid hydrocarbons. Finally, there will be a separation stage to allow the hydrocarbon mixture produced from the FT reaction to be separated into the required fuel fractions.
2. The pilot plant was to provide as far as possible a versatile pilot plant which could support production of base hydrocarbons in the aviation fuel range via a range of RWGS and FT catalysts which are generally used for this process. The catalysts which have been selected through a supply partner should see better performance in comparison, thereby providing the University with the ability to trial alternatives in the future.
3. Finally, in addition to the major unit operations, there must be ancillary equipment for emergency shutdown to a safe state, regeneration of the catalysts, gas mixing, prevention of catalyst contamination, compression, heating and cooling of reactors and process sampling.

Outline Process Description

The following are to be considered as logical steps in the process

1. The gas feed to the plant depends on the running mode selected. Either CO2 and H2 can be fed to the RWGS reactors to produce syngas, or biomass syngas and H2 can be directly fed to the FT reactor. The inlet gas pressures are either raised or reduced to meet the onward demands of the process.
2. The CO2 or biomass syngas is directed to the gas clean up module designed to remove trace amounts of contaminants. This consists of a heated alumina bed to remove metal carbonyls, followed by three activated carbon beds to remove organics, sulphur and amines respectively. Finally, the gas is passed over a heated Copper Oxide and Zinc Oxide catalyst bed for removal of SO2 and O2. The clean gas is compressed, if the plant is running in CO2 mode it moves to step 3. If the plant is operating in biomass syngas mode it moves to step 8.
3. The RWGS feed gas is then mixed using mass flow controllers and a static mixer, a small Nitrogen volume can be blended into the feed stream during this step to act as a tracer for analysis.
4. The gas is fed to the Stage 1 RWGS reactor, where it passes through a pre-heater to reach reaction temperature and then moves through the catalyst bed for production of a CO and H2 mixture.
5. The product from the Stage 1 RWGS reactor is cooled for condensation and removal of water.This stage shifts the reaction equilibrium and allows greater conversion of CO2 to CO in the second stage. A 1:1 recycle can be employed within the Stage 1 RWGS reactor.
6. The Stage 1 product gas is fed to the Stage 2 RWGS, along with a further top up of CO2.

7. The product from the Stage 2 RWGS reactor is cooled for condensation and removal of water. A 1:1 recycle can be employed within the Stage 2 RWGS reactor. This water removal allows for more efficient compression downstream of this stage and serves to protect the FT catalyst.
8. The Syngas composition is then adjusted using Nitrogen and Hydrogen. This is done via mass flow controllers and a static mixer.
9. The gaseous mixture (Syngas) is compressed to the FT reaction pressure then mixed with the FT gaseous recycle from the cool separator at a ratio of up to 3:1 recycle to fresh feed.
10. The gas is distributed evenly between the FT reactor tubes. An orifice plate is used to drop the pressure and allow even distribution between each tube. The reactor tube consists of a pre-heating section to bring the gas up to reaction temperature and the FT catalyst bed.
11. The FT product is fed to a hot three-phase separator. The aqueous layer is removed via the bottom of the separator, the liquid hydrocarbon layer is removed from the middle of the separator and the gaseous phase is removed from the top of the separator.
12. The gas from the hot separator is fed to a cool three-phase separator. Any remaining aqueous layer is removed via the bottom of the separator, the liquid hydrocarbon layer is removed from the middle of the separator and the gaseous phase is removed from the top of the separator. The gaseous output from the cool separator is the recycle stream fed in at step 9.
13. All aqueous streams from the plant are fed into an aqueous receiver, which can then be fed to a waste drum. The liquid hydrocarbon layers from the hot separator and cool separator are fed into a hydrocarbon receiver which is kept at increased temperature to prevent solids forming. There is a continually pumped loop from the bottom of the hydrocarbon receiver feeding back into the top to further aid mixing and prevention of solid formation.
14. As required, the liquid hydrocarbons from the hydrocarbon receiver will be fed to a distillation stage for separation of jet fuel from other fuel fractions.

Procurement and Legal Compliance

The rig was tendered via the full OJEU procurement process in accordance with Public Contract Regulations 2015. Furthermore, additional procurement regulations imposed by European Regional Development Fund, as a project partner were complied with.

Principal Contractor Company Description, Financial Status and Background

Strata Technology Ltd (Strata) won the design and build contract to supply University of Sheffield (UoS) with a turnkey Sustainable Aviation Fuels Production Facility, for installation in the Translational Energy Research Centre (TERC).

Strata specialise in the design, build, installation, commission and after-sales support for laboratory-scale equipment, skid-mounted rigs and pilot plants used for R&D, proof of concept, process scale-up or production purposes. They aim to develop tailored solutions based around customer budget requirements and needs and have designed and built many bespoke products solving a wide range of specific challenges.

Strata has designed and built bespoke laboratory-scale equipment, skid mounted rigs and pilot plants used for research, process development or small-scale production since its inception in 1998. They claim to operate a Business Management System (BMS) approved by Lloyd's Register (LR) Quality Assurance Ltd to be compliant with ISO 9001:2015, ISO 14001:2015 and ISO 45001:2018. LR also audits Strata's BMS annually. Strata has also an approved Fit For Nuclear (F4N) business since 2016.

History of Project Events

In order to inform the technical specification development for the invitation to tender (ITT) document, market consultation commenced in late 2018. At the time, the market assessment and resultant design specification development was considered a success, with a number of potential bidders identified and an outline developed by the internal project team. The design was further refined to meet the objectives of the grant and the estimated tender value of £784,000 was established. However, the process was delayed due to challenges obtaining feedback from the market resulting in a 3 month shift in the project programme.

The design and specification was used to develop an ITT by the project team's academic theme leader in collaboration with the University of Sheffield Procurement Department. The ITT was formalised, enabling a full OJEU compliant tender to be developed and the ITT was eventually released 01/11/2019, with a forecast closure date of 03/12/2019.

The tender period played out as planned with minimal clarifications received from the market. However, during the tender phase, Strata Technology Ltd contacted the University to request an extension, which in turn was granted to 05/01/20.

On completion of the tendered period, unfortunately, despite the comprehensive research undertaken during the market consultation phase and several expressions of interest, only one company returned a formal bid. Furthermore, this lone bid (submitted by Strata Tech Ltd) significantly exceeded the estimated budget by 263% (£2,115,300).

It is believed that this variance was due to an underestimate of the complexities of the pilot plant in general by the University of Sheffield team. Furthermore, the addition of the novel reverse water gas shift reactor was selected as described in section 1, 2 and 3.

After a 3 month tender clarification phase and contract variation of both the BEIS and ERDF grant funding agreements the expenditure was justified and granted. The final contract was awarded for £2,064,000 to Strata Technology Ltd on 19/03/20.

The first COVID-19 wave and associated lockdown commenced 23/03/20. Despite this the Project Kick off meeting was undertaken virtually on 26/03/20. Initially communication was good and the project teams (University of Sheffield and Strata) met bi-weekly to progress the design. The preliminary design review (PDR) was completed on 14/07/20 and the final design review (FDR) on 24/09/20. Both were undertaken face-to-face under enhanced COVID measures.

At this stage it was understood that the design would be finalised to allow procurement and fabrication to commence. However on reflection, whilst it is accepted that the outline design was finalised at this point, further detailed engineering design continued in parallel to procurement and fabrication. This resulted in a lack of oversight from a design perspective by the University of Sheffield technical team. This, combined with various challenges associated with COVID-19, resulted in Strata drifting from the agreed programme.

Project Management oversight continued bi-weekly, however the programmed design development phase continued to drift. The UoS project team awarded 2 contract variations on 18/06/20 and 29/06/21, with project completion forecast of June 2021 and December 2021 respectively.

Strata explained that the reason for these delays was due to the addition of the requirements identified during design and safety reviews, including enhanced DSEAR/ATEX measures and the requirement for a flare to expel the off gases, which in turn resulted in Strata naively agreeing to take on additional work at risk to the programme and for no additional costs. This included:

- Replacing our originally proposed Solid Fuel Oxide Stack with two-off custom designed and built Reverse Water Gas Shift Reactors
- Having to design and purchase equipment to meet ATEX Zoning requirements, when we had originally planned to work to Safe Area principles
- Increasing the flexibility of the plant to accommodate different catalysts and additional sampling capabilities which significantly increased complexity and added additional hardware we had not budgeted for

However, in September 2021 Strata informed the UoS that not only was the revised delivery date of December 2021 not achievable, but the project budget was at significant risk. Furthermore, Strata Tech Ltd were of significant risk of entering into liquidation should the budget not be increased to accommodate the variations identified above. Moreover, Strata realised that the effort required to design a CHP engine to manage the off-gases (the final remaining fundamental element of the design) resulted in approximately 6 months additional work. Strata stated that a commercially available CHP engine that would meet the various gas makeup cases could not be found on the market and therefore was not viable. Following consultation with the Environment Agency (EA) led by the UoS, the originally proposed flare solution was accepted.

In addition to this specific challenge, Strata had faced unprecedented circumstances relating to Covid-19, both directly in terms of the utilisation of engineering resources in an efficient and effective manner and indirectly in terms of the availability and cost of equipment.

At this stage the Uos took the difficult decision to freeze the account and ordered Strata to undertake a full financial and technical project review. An independent technical consultancy, JBA Engineering Ltd, was employed by the UoS to review the status of the project. JBA concluded:

- The tender approach used by TERC was not sufficiently detailed to allow fixed price bidding, and the timescale allowed for bidding was too short.
- Strata did not allow sufficient contingency in their proposal based on the level of detail and timeframe allowed in the tender, indicating that the tender cost of £2.064m was not sufficient at this scale (1-1.5L/h), refer to section
- A significant amount of change was introduced at pre-award and it is likely that this change impacted the overall cost and schedule, refer to section
- Strata have indicated that they have achieved the engineering milestones, however there is no documented evidence that these have been achieved, refer to section
- Strata's project management is inadequate, and the technical and engineering disciplines are disjointed, and this is causing the gross cost and schedule increases on the project, refer to section
- There is evidence that the process has been over designed leading to delays and overspend, refer to section
- Strata have not presented sufficient engineering documentation for the stage of the process.

In parallel the UoS conducted an options appraisal which resulted in two viable options:

1. Continue the project with Strata Technology Ltd by increasing the budget and programme via formal contract. This option would also include additional oversight in the form of independent technical, financial and legal support.
2. Terminate the contract with Strata Technology following a period of asset and intellectual property acquisition. To re-tender for the project for open formal tender.

Regardless of the option chosen, it is recognised that a budgetary increase is necessary to complete the project. Therefore, in parallel the project sought to identify alternate sources, both internally and externally of funding.

Strata confirmed in December 2021 that 8 weeks would be required to produce the technical and project documentation to a standard that had been defined as acceptable by the UoS. Strata produced a phase project plan which resulted in a submission of the required documentation on 11/02/22.

At the time of writing this document Strata had achieved the submission deadline and the UoS project team were in the process of evaluating the submission. The proposed project plan to conclude the project is detailed in Figure 2.

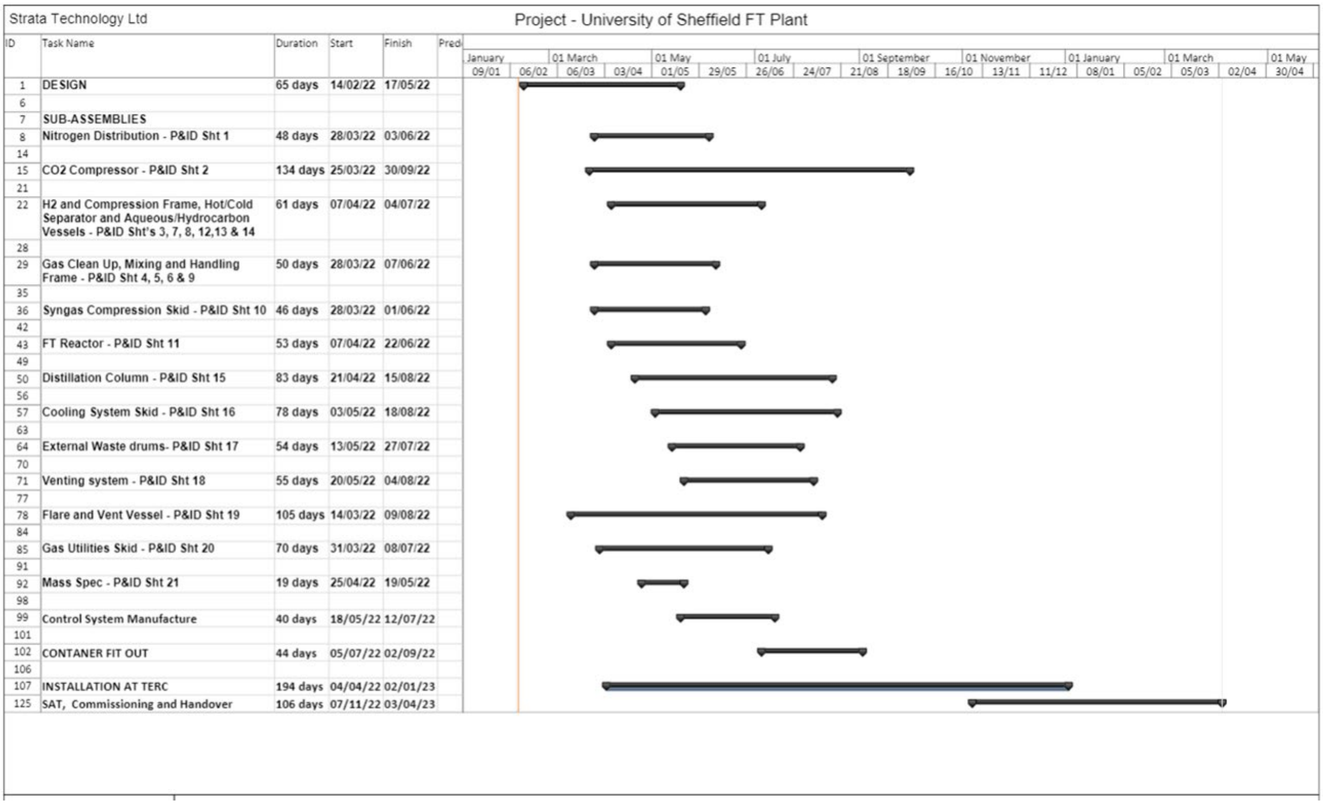


Figure 2: SAF - Project Programme

Project Budget, Actual vs Forecast

A fixed cost contract of £2,064,000 was issued under Purchase order XJ0 / 4501083056 on 23.03.2020 under the Strata project no of 20/0026/02.

As of March 2022, there have been no additional increased costs to the original budget as the contract is for a full turn key installation. However, as outlined above in the project events section, it has been advised by the principal contractor that there is forecast overspend of an unknown quantity required to complete the project.

Project Milestones, Actual vs Forecast

Task	Forecast Completion	Actual/Forecast Completion
Market Consultation	June 2019	September 2019
specification development	June 2019	October 2019
Tender development	July 2019	November 2019
Tender period	September 2019	December 2019
Evaluation period	October 2019	March 2019
Project Kick Off	November 2019	March 2019
Design Phase (including Outline design and detailed design)	January 2020	May 2022
Fabrication Phase	August 2020	July 2022
Installation Phase	October 2020	January 2023
Commissioning Phase	Feb 2021	April 2023

Key Lessons Learnt

- The UoS project team recognises that whilst a significant and extended period of market consultation was conducted, the resultant design specification, combined with estimated project budget, was not accurate, as this exercise only resulted in one bidder. Whilst the specification provided by the lone bidder did appear to meet all the technical requirements, the price significantly exceeded the anticipated budget. The project team has therefore concluded that the design, development and market assessment phase of technologies of this size and complexity warrants additional external specialist engineering and commercial support in the future, as the strength and maturity of the design specification and the accuracy of the market assessment significantly influences the competitiveness of the procurement exercise. This, in turn,increases the likelihood of identifying a suitable principal contractor, which reduces the project risk and improves the likelihood of a successful design and build project outcome.
- The tender period was far too short for a project of this size. At the time, the decision for a relatively short tender period was based on maximising the period for design and build, whilst ensuring the ability to meet project deadlines. It was realised during the tender phase that longer was required in order to allow bidders to time properly assess the requirements and submit a comprehensive bid, hence the considerable tender extension was provided. However, it is difficult to predict the number of potential vendors lost at the outset that may have considered a bif of the tender period was longer in the first instance.
- Despite the extended tender period only one bid was received. This is likely due to the fact the budget was considerably inadequate and the original tender period far too short. Furthermore, the lack of technical detail in the ITT may have discouraged potential bidders. The project team learnt from this at the time and carried more formal design work upfront for inclusion in the ITT specification. Thereby closing the scope of the project and making it easier for companies to competitively price.
- At contract award Strata’s financial status was comprehensively studied and the project team found no cause for concern. Furthermore, due to regulations the project team could not interrogate Strata’s proposed budget breakdown. However, the UoS project team recognised that the ITT should have included a more detailed cost table, thereby requiring bidders to break down the budget proposal in more detail, and in turn enabling the budget to evaluate more closely for accuracy and adequacy. This may not have resulted in Strata’s proposed insufficient contingency.
- The proposed introduction of the RWGS reactor, which was introduced at pre-award, resulted in Strata naively not considering the time and budget required to introduce such a technology. The project recognises that in the future any change introduced post ITT issue may be a compliant practice but does introduce a significant technical risk.
- Strata have continuously indicated that they have achieved the engineering milestones, however on several occasions Strata would identify technical challenges resulting in a change of design of elements of the rig. This in turn has resulted in a perpetual cycle of internal design changes, which have had significant programme and financial consequences. Whilst the project team established a clear tangible milestone that included stage payments associated with design, Strata continued to make internal, non-disclosed tweaks to the design. Due to the extremely tight timescale the project team chose to continue with the other milestone, in order to ensure the project remained on programme. However, it is clear that in the future design milestones must be policed and adhered to rescue scope drift, regardless of any short term impacts to the programme.
- As an SME, various independent consults have recognised that Strata’s project management practises are inadequate, and the technical and engineering disciplines are disjointed, and this is causing the gross cost and schedule increases on the project. The project team recognised that this could have been identified at the tender evaluation stage by included criterion and

associated marks for evidence of project management process, experience and examples of relevant projects.

Molten Carbonate Fuel Cell

This section details all the key project metrics and provides a factual based narrative of the project's historical events and key lessons learned. With the aim of advising the reader of the challenges experienced in projects of this kind.

Original Project Design Intent

The Molten Carbonate Fuel Cell (MCFC) combines CO2 capture with electricity cogeneration. The unit was intended to be interfaced with all combustion plants (through the flue gas manifold system) for post-combustion capture as well as with the ACP and MCP for treating of CO2-enriched gases generated by the MCFC, and ultimately with the CCU plant(s), thereby providing full CCUS chain integration. The Gas Mixing Facility (GMF) will also be connected to provide a platform for research and system optimisation. Hydrogen required for the process will be supplied from the site electrolysers powered from renewables or other onsite generation. Furthermore, it is possible to operate the MCFC with syngas. The process gas will be provided as either a synthetic mixture from the GMF or directly from the biomass gasifier, once emissions and clean up procedures have been addressed. TERC also plans to set up an integrated system with one of its gas turbines (GT1) for gas operation.

The ability of MCFCs to cogenerate electricity whilst capturing CO2 is a significant advantage over other capture systems, although they require hydrogen for the process. The system opens up many opportunities for R&D work, both on system optimisation and the assessment of impact of impurities and corrosion on the MCFC itself, and also on system integration into gas turbine cycles. R&D in this field will benefit OEMs working in this area as well as manufacturers of gas turbines, reformers, gas clean-up and other system components.

Final Project Design Outcome

The successful bidder Fuel Cell Energy (FCE) proposed a 30kW MCFC demonstration module based on the design and sizing of their own internal R&D pilot facilities. The 30kW scale meets the criteria of the ITT and fits well with the TERC infrastructure and other pilot scale facilities. The fuel cell materials and stack design are the same as those deployed in FCE’s commercial products, except for utilising fewer cells (30 compared to 400 cells/stack).

The 30 kW Subscale Test Module is a robust test platform for full area MCFC development. The module contains the high temperature fuel cells, each of which are the same size as used in product fuel cell stacks, however the number of cells in the stack is reduced significantly. The following comprise the primary functions of the subscale test module:

- Physical containment and thermal insulation of the high temperature fuel cells
- Interfacing between process gas piping and the manifolds of the fuel cell stack, including pressure boundary for cathode flush inlet
- Mechanical compression of the fuel cell stack as well as gas manifolds to the stack
- Electrical interface between the fuel cell stack and electrical balance of plant
- Harnessing and providing interface for high volume instrumentation

The exterior structure of the module consists of a two-piece dome and base concept. The dome is removable from the base for assembly access and contains a majority of the thermal insulation. The base consists of the fuel cell stack itself, the compression system, the piping interfaces, the instrumentation harnesses and thermal insulation to provide a lower temperature 'purgatory zone' allowing for lower temperature instrumentation and mechanical equipment. The diameter of the circular module is 84" and the weight of the module is 15,000 lbs., distributed between 3,650 lbs. for the dome and 11,350 lbs. for the base with fuel cell.

Procurement and Legal Compliance

The rig was tendered via the full OJEU procurement process in accordance with Public Contract Regulations 2015. Furthermore, additional procurement regulations imposed by European Regional Development Fund, as a project partner were complied with.

Principal Contractor Company Description, Financial Status and Background

FuelCell Energy (FCE) Inc. is a global leader in fuel cell technology with a purpose of utilising its proprietary, state-of-the-art fuel cell platforms to enable a world empowered by clean energy. FCE provides comprehensive turnkey solutions that include everything from the design and installation of a project to the long-term operation and maintenance of the fuel cell system. They supply the leading global fleet of 'SureSource' power plants, which span three continents and are leading the industry with millions of megawatts of ultra-clean power produced. Utilising state-of-the-art fuel cells, the SureSource plants provide environmentally responsible solutions for various applications such as utility-scale and on-site power generation, carbon capture, local hydrogen production for both transportation and industry, and long duration energy storage.

History of Project Events

In order to develop a successful specification and tender, market consultation commenced in late 2018 and at the time was considered a successful phase in the wider project, with a number of potential bidders identified. The outline design was refined to meet the objectives of the grant and the estimated tender value of £337,316 was established.

A tender specification was developed by the project team's academic theme leader. The specification was formalised, enabling a full OJEU compliant tender to be developed by the University of Sheffield Procurement Department. The ITT was released 05/02/2020, with a forecast closure date of 18/03/2020.

The tender exercise resulted in 2 returns: Fuel Cell Poland and Huaneng Clean Energy Research Institute. However, despite the comprehensive research undertaken during the market consultation phase, which resulted in a comprehensive tender specification and several expressions of interest, both tenders were considered technically inferior to the required specification. In summary, both tenders did not provide a detailed proposal that covered all aspects of the technical requirements. Furthermore, there were considerable doubts as to the bidders' technical competence and experience to deliver a rig of sufficient scale and complexity.

Following a period of detailed evaluation and consideration, the decision was made to reject both submissions and the tender exercise was formally closed on 21/05/20.

The project team sought to revise the technical specification of the tender and to inform all market leaders of the technology of the tender via advertisement, with a view to maximise the possibility of positive outcome. Eventually, this resulted in a second tender exercise, with an ITT published on 02/07/20, with closure date of 18/08/20.

The tender period closed as scheduled with one bidder, Fuel Cell Energy. Clearly this was less than hoped, however as a market leader in this technology it was clear the Fuel Cell Energy's submission met all the technical requirements as defined in the original design scope and grant funding agreement. Therefore the evaluation period was relatively swift and the intention to award notice was issued shortly after evaluation. However, due the proprietary nature of the technology and FEC's concerns regarding IP and the University's intended use of the research apparatus, the contract required significant amendment. The contract was developed in collaboration with FCE, FCE's legal team as well the UoS Project Team and the UoS legal teams. Ultimately this scrutiny and the level of detail required resulted in a drawn out contract negotiation period, which took over 9 months. The contract was eventually signed 30/06/21, 17 months after the original project procurement activities commenced.

Specifically the challenges associated with IP included:

- The specific elements of the system to which each party retains full, partial, shared and no intellectual property rights.
- The parties acknowledgement of future research projects and future collaboration. In this instance the parties agreed the University will consult with the Supplier and offer Rights of First Refusal ("ROFR") to participate in the project and/or join the consortium, with a defined period of time. In the event of the Supplier declining ROFR the University will protect all Background IRP and will prevent any other party obtaining right, title or interest in such Intellectual Property Rights unless otherwise agreed in writing between the Parties.
- The University's right to publish research findings. In this instance the parties acknowledge that the University will maintain publishing rights. However, said publishing must not result in or lead to any breach in the NDA between the parties. In any/all cases FCE will be consulted in

advance and draft paper will be made available to FCE before any formal submission to journal, conference or any other publication is made.

With regard to the contract budget, for the main module and some elements of the supporting system equipment only, the budget equated to £871,631.00 which is 258% above the original forecast value. This does not include the support infrastructure costs, which at the time of writing this report were unknown, but forecast to equate to £268,000. Therefore, the project team estimates the final balance could be circa 400% above the original conceptual market research.

Since contract award the UoS project team and FCE project team has worked collaboratively to develop the wider system technical integration design. The teams have met bi-weekly and at the time of writing this report, 12 technical design meetings have taken place.

In parallel to the design process, FCE commenced fabrication of the 30kW module in July of 2021. The module was completed without any reportable issues in September 2021. The rig was shipped the following Month and arrived at TERC in January 2022.

The project team has now finalised the P&ID and the project team has employed an independent engineering team to work up the design in order to release a formal open tender and to procure the relevant component parts.

Figure 3: MCFC Installation

Project Budget, Actual vs Forecast

The original project budget was based on a fixed price of £265,000.

However, following market consultation and two invitation to tender procurement attempts the budget was finalised as follows:

Item	**Cost (Ex VAT)**	**Cost following application of appropriate VAT**
MCFC Module and 3 additional ancillary items (Procured from FCE)	£871,631.00	£871,631.00
Additional ancillary items (Budget)	£ 268,000.00	£ 268,000.00
Total	**£ 1,139,631.00**	**£ 1,139,631.00**

Project Milestones, Actual vs Forecast

Task	*Forecast Completion*	*Actual/Forecast Completion*
Market Consultation	*June 2019*	*September 2019*
specification development	*June 2019*	*December 2019*
Tender development	*July 2019*	*February 2020*
Tender period	*September 2019*	*March 2020 (first tender)* *August 2020 (second tender)*
Evaluation period/Contract award	*October 2019*	*May 2020 (first tender)* *June 2021 (second tender)*
Project Kick Off	*November 2019*	*June 2021*
Design Phase (including Outline design and detailed design)	*January 2020*	*Jul 2021*
Fabrication Phase	*August 2020*	*Sep 2021*
Delivery	*September 2020*	*January 2022*
Installation Phase	*October 2020*	*July 2022*
Commissioning Phase	*Feb 2021*	*September 2022*

Key Lessons Learnt

- This project highlighted more than any other the cost associated with installation and integration of the various technologies in order to build the infrastructure that is required to setup next generation facilities. For example; The predicted cost of MCFC module was approximately £350K and the final cost was £450k. However, the cost of infrastructure required, which was spread over various budgets exceeded £1.3M in total. In this example this included; gas cleaning, gas separation, control system and so. Therefore, projects teams looking to procure, install and commission integrated technologies such as these should apply significant attention to the ancillary cost associated with the wider installation.
- The UoS project recognises that whilst a significant volume of market consultation was conducted prior to the release of the ITT, the project team significantly underestimated the cost of the MCFC system. As highlighted in previous procurement exercises conducted by the project team, the project team would have benefited from additional external technical design and market assessment support in order to establish a more in-depth and informed market assessment period to tendering for the apparatus. Whilst the project team has been impressed by the performance of the principal contractor, by establishing a higher quality initial specification the project team has avoided the failed procurement exercise and the need for a second. Thereby saving time in the programme in the long run.
- The tender period for the first tender was far too short for a project of this magnitude. At the time, the decision for a relatively short tender period was based on maximising the period for design and build, whilst ensuring the ability to meet project deadlines. Furthermore, the existence of the tender was not advertised to the relevant parties. Both these factors may have contributed to the unsuccessful procurement exercise which resulted in two inadequate bids.
- For the second tender the project team further enhanced the technical specification, extended the tender period and advertised the existence of the tender to a range of relevant stakeholders. Despite this the procurement exercise still resulted in just one bidder. The project team recognises that this may simply be due to the proprietary and novel nature of the technology. Hence, it is important to recognise that open tender procurement is a challenging activity made even more difficult when tendering for technologies which are novel and complex.
- Despite improved learnings, achieved due to the two tender specification periods and the additional market consultation, the project budget was still woefully short. It is recognised that changes in the supply chain as a result of factors such as Brexit and Covid-19 may have contributed to the extreme variation. However, in truth the vast chasm in budget was due to the lack of understanding in technology and its complexity at the concept phase. Therefore, this further highlights the importance of detailed and comprehensive market assessment at the concept phase.
- Whilst the second tender exercise returned a successful proposal following detailed evaluation, the negotiation contract period was extremely protracted. A contract period of >9 months is very unusual, however as identified above this was due to the nature of the technology and concerns regarding the intellectual property rights. Therefore, the project team recognises that contract negotiation periods for complex technologies needs to be considered when scheduling projects at the concept phase. Especially as the project team is not of the opinion that this period could have been reduced by taking a different approach.

Shocktube, Chemical Kinetics Test Facility

This section details all the key project metrics and provides a factual based narrative of the project's historical events and key lessons learned, with the aim of advising the reader of the challenges experienced in projects of this kind.

Original Project Design Intent

To complement the research conducted in the High Temperature High Pressure Heat Exchanger Test Bed (HEX rig), TERC will also include a high pressure shock tube with analytical ports for fuels chemical kinetics research. A shock tube is a cylindrical tube of two distinct sections, the driven and the driver section, which are separated by a thin metal diaphragm. The driven section is filled to a lower-pressure (max 10 bar) and contains a fuel and oxygen mixture, diluted in an inert bath-gas. The driver section is then pressurised using an inert gas such as helium, argon, or a mixture of the two. Once the pressure difference across the diaphragm is too great, the diaphragm ruptures, generating a shock wave which propagates down the driven section of the tube, heating and compressing the test gas as it goes. This initiates the combustion reaction which is studied close to the endwall of the driven section using various laser diagnostic equipment. The shock tube will be installed as a standalone experimental enclosure as shown in figure 1 and figure 2 which shows the shock tube test bed layout. The driver gases (helium and argon) and the driven gases (methane, hydrogen, oxygen, nitrogen, carbon dioxide and argon) will be supplied over a bridge and via a mixing manifold as shown in figures 1 and 2. The shock tube will need to be mounted off of the ground at around 100 cm to allow routine maintenance and operation. Due to the rupturing process of the diaphragm, it will need to be replaced between every experiment, this means the driver section will need to be movable to allow regular access to the diaphragm section to recover the ruptured diaphragm and replace.

Figure 4: Shocktube Installation (Example)

Final Project Design Outcome

Shock Tube and Gas Mixing Facility

The successful bidder, Heblac Technology Gmbh, proposed a stainless steel shock tube with an inner diameter of 101.6 mm, a total length of 10.7m and a working pressure of 500 bar@ 125°c.

The system includes a weighted stand (filled up with concrete) for stability and an overall length of 11m, height of 1m and width of 0.5m. A Manifold for gas mixing and filling of shock tube and mixing vessels including rotary vacuum pump, not included: connection to gas support, connection to exhaust lines, heating system. A 200L (@60bar) Mixing vessel, made of stainless steel,

Furthermore, the system includes a data recording system containing a measuring PC with data acquisition card and constant current power supply for the 8 system piezo sensors.

The dynamic pressure sensors, measurement range (for ±5V output) 344.75 bar, useful overrange (for± IOV output) 689.5 bar, maximum pressure 1034.25 bar, resonant Frequency > 500 kHz, rise time < 1 μs, maximum operation temperature 135 °C

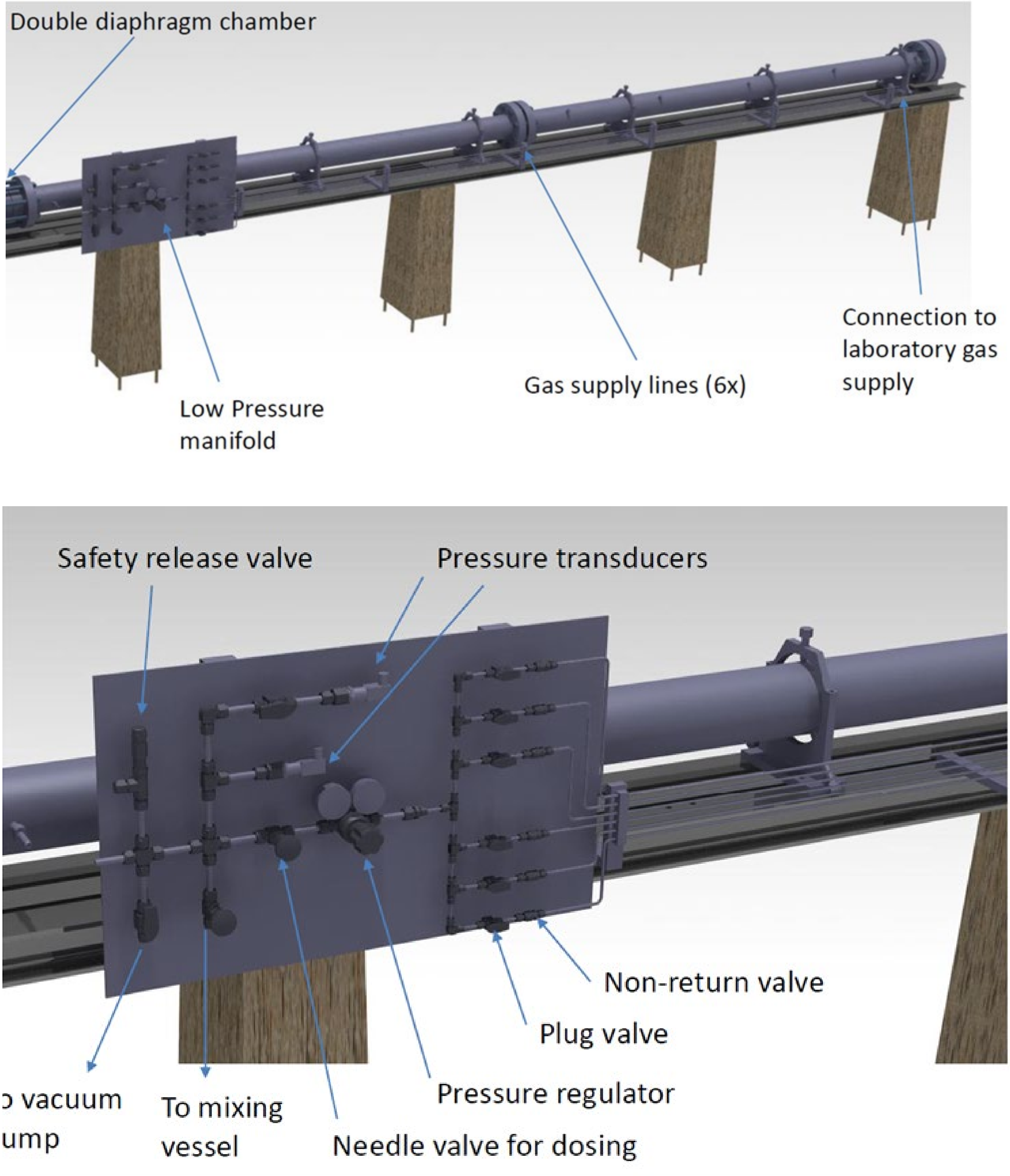


Figure 5: Shocktube Installation (Designs)

Laser Diagnostic System (NIR seed laser)

An award-winning SolsTiS is a next generation continuous-wave Ti:Sapphire laser was selected and distributed by M Squared Technologies. The seed laser is designed to meet the needs of pioneering scientists looking for high performance, ease of use, system flexibility and reliability. The fully-automated, compact system features a completely sealed, alignment-free cavity with hands-free operation – together with an unprecedented tuning range, unrivalled power and a low-noise output of extremely high spectral purity. The seed laser provides tuning in the fundamental NIR spectral range from 700-1000 nm. This includes a 15 W Equinox pump laser – enabling average output powers of > 4W at the peak of the fundamental NIR tuning curve. The Equinox is a low-noise, single-frequency, CW DPSS laser - with an average output power of 15 W at 532 nm and a linewidth of < 1 MHz. The Equinox has been designed for a range of scientific and industrial applications including the pumping of any Ti:Sapphire laser system. It has been carefully engineered to meet the needs of customers requiring high-performance systems with an emphasis on reliability, stability and ease of use. The laser incorporates pump diodes within the central unit and is fully automated with hands-free operation and control via an Ethernet interface (TCP/IP commands), an intuitive web browser based Graphical User Interface (GUI) webpage. It is a completely sealed system and is inherently stable with low noise levels EMM-532-SFG-A wavelength extension module (306-310 nm).

A wavelength extension module is required to generate UV output from 306-310 nm. This module is known as the EMM-532-SFG-A; this uses Sum Frequency Generation (SFG) to mix the NIR output from the SolsTiS seed laser with the single-frequency 532 nm output from the Equinox pump laser (via high-efficiency, single-pass transmission through a non-linear optical crystal). As configured, this wavelength extension module will provide automated wavelength tuning from 306-310 nm. This module can be upgraded to extend the tuning range to 302-347 nm (if desired). Please see the attached quote for the associated costs (Extended Tuning Upgrade). This all-solid-state solution is fully automated. All the required nonlinear crystals are designed to be mechanically translated, phase matched, adjusted and optimised without any manual adjustment. The SolsTiS EMM-532-SFG-A is the only system available on the market that can offer this tunability, automation and spectral output. It delivers unparalleled performance and reliability, enabling tuning and scanning over a broad wavelength range.

Figure 6: M Squared Laser Diagnostic Equipment

Procurement and Legal Compliance

This Shock Tube facility benefited from being the last item of the first round grant funding arrangements procured under the TERC programme. Therefore, this equipment in particular benefited significantly from increased experience gained within the project management team. Specifically, the project team aimed to increase the quality and technical accuracy of the tender specification by employing a consultant to assist with the full system design. Furthermore, the project team decided to divide the system into two to capitalise on the specialism of different suppliers and move one step away from a full turnkey solution:

1. Shock tube and mixing facility
2. Laser diagnostic equipment

WSP Ltd, a engineering design consultancy company, were employed (for £24500) to produce the full engineering design for the system. A task that took approximately 4 months from issue of the RFQ and 3 months from contract award to final design delivery. In addition to providing design specification, WSP were tasked with carrying out a market assessment of potential suppliers. Both aspects of the contract were delivered to a high standard by WSP, resulting in a high quality tender and an understanding of potential market raiders. All of which contributed to a very high quality specification and ITT.

WSP Ltd, a engineering design consultancy company, were employed (for £24500) to produce the full engineering design for the system. The task of employing them took approximately 4 months from issue of the RFQ and 3 months from contract award to final design delivery. However, following the technical evaluation, it was also concluded that none of the bidders provided a bid that met all the technical requirements. This was particularly disappointing, given the effort to develop a strong tender. However, during a technical specification development, the academic team developed links with researchers at the Stanford/KAUST team with the UOS team. This led to a relationship being forged with a company called Heblac Technologie Gmbh. Following consultation with the University of Sheffield procurement department it was agreed that a single source tender could be conducted, subject to the release of a VEAT (Voluntary Ex-Ante Transparency) notice. This was issued in August 2021, following nill correspondence from the marketplace, in September 2021 the UoS agreed that Heblac Technologies Gmbh could be contracted via a compliant single source procurement exercise.

For the laser diagnostic equipment, the project team used additional expertise in the University, including the Department Laser Safety Officer to assist with the procurement of the laser diagnostics equipment. The laser diagnostic equipment was tendered via the OJEU procurement process as per PCR 2015 legislation. Furthermore, as per all other procurement activities, this project was also part-funded by the European Regional Development Fund and therefore subject to further specific procurement legislation.

Principal Contractor Company Description, Financial Status and Background

Shock Tube and Gas Mixing Facility

The Shocktube and gas mixing facility was supplied by Heblac Technology Gmbh. The company was founded in 1999 and they focus on tailor-made solutions and bespoke projects. They focus on the manufacture and coating of complex components in multi-stage manufacturing processes. This includes processes such as: water jet cutting, milling and boring machine processing, annealing and heat treatment, grinding processing, surface coating (e.g. chemical nickel, boriding or plasma nitriding) for a wide range of product types and sizes across a wide range of industries.

The company is considered to be an SME by UK standards and boasts an impressive backlog of historic and appointed projects.

Laser Diagnostic System (NIR seed laser)

M Squared lasers (M^2 Lasers) are an award winning photonics and quantum technology company. They produce a range of laser platforms, designed to to be used in the scientific and research industry. A global company, they are well established in the UK and highly regarded as a leading developer of photonics and quantum technology. Their light-based applications are used in a number of fields, including quantum technology, biophotonics and chemical sensing. Their products span a wide range of sectors including advanced manufacturing, oil and gas research, space technology and the medical sectors.

Incorporated in 2003, M^2 lasers have grown significantly over the past decade boasting a turnover of £14M and profit of £6M in 2020.

History of Project Events

Following internal research of similar systems it was identified that additional external engineering support would be required to develop a suitable tender. A simple request for quotation for engineering design services to support with the development of the specification was released. WSP Ltd was identified as the most suitable company. They were contracted in October of 2019 and works commenced shortly thereafter. The University of Sheffield project team met weekly to support WSP develop the specification. In addition, WSP were also tasked with identifying suitable companies capable of developing a rig to the standard required. The report was delivered 25/01/21 and included a detailed design specification. Following some technical clarification the final report was received on 15/2/22. This submission also included the vendor list, which included circa 25 potential vendors organised by particular areas of expertise. Unfortunately, no singular vendor was proposed that would be able to deliver all aspects of the project, despite the significant research conducted by WSP Ltd. Therefore the decision was made to split the project into 2, with the Shock Tube and mixing facility procured separately to thrasher diagnostic equipment.

Shock Tube and Gas Mixing Facility

The tender was released 12/03/2021 with a closure date of 12/04/2021. In total there were 7 expressions of interest. However, only three submitted formal bids; FTT Uk, HRS Energy and KGD. However, following evaluation it was identified that all three significantly exceeded the budget. Furthermore, following the technical evaluation, it was also concluded that none of the bidders provided a bid that met all the technical requirements. This was particularly disappointing, given the effort to develop a strong tender.

However, during a technical specification development, the academic team developed links with researchers at the Stanford/KAUST team with the UOS team. This led to a relationship being forged with a company called Heblac Technologie Gmbh. Following consultation with the vendor and with advice from the University of Sheffield procurement department the project team contracted Heblac Technologies Gmbh via a compliant single source procurement exercise. A procurement method of this kind was necessary given the time left in the project programme to deliver this piece of equipment as discussed above.

Following the formal issue of the contract on 06/09/21 a kick off meeting was held with Heblac 13/09/22. At this meeting the contracted delivery date of 30/05/22 was confirmed via a detailed programme. Since this date the project team has met regularly with several progress/interim reports submitted by the vendor.

At the time of writing this report the TERC project team and Heblac continue to work towards a delivery date of May 2022.

Laser Diagnostic System (NIR seed laser)

In parallel to the procurement of the shock tube itself, the laser diagnostic equipment was also procured. Following a tender specification development phase the tender was released 13/01/2021 with a closure date of 12/02/2021. In total there were 2 expressions of interest. However, only two submitted formal bids; Coherent Uk and M Squared Lasers. Following a period of clarification with both bidders, it was established that the MSquared laser proposal met all the essential technical requirements and the package proposed was on budget.

A formal contract was issued 3 months after the tender submission date due to the need to establish that sufficient budget was available for the shock tube facility as a whole was remaining in the project.

This was established by allowing the procurement activity running in parallel to run its course as described above. Eventually, once the technical solution for the shock tube itself was established the contract for the laser diagnostic equipment was issued on 06/06/21 and a kick off meeting was held with M Squared Lasers on 11/06/22. At this meeting the contracted delivery date of 30/12/21 was confirmed via a detailed programme. All items of equipment were received in December 2021. However, at the time of writing this report as the shock tube facility had not yet been delivered, the laser equipment lay in storage in anticipation for commissioning in May 2022.

Project Budget, Actual vs Forecast

The project budget established at the grant funding stage was based on a combined budget for both High Pressure High Temperature Heat Exchanger Test Bed (HEX) and Shocktube system of £1,487,220.

Following design tenders and split down of the project the final project costs are as follows.

Item	***Cost (Ex VAT)***	***Cost following application of appropriate VAT***
Shocktube and gas mixing facility	*£ 315,376.00*	*£ 315,376.00*
Laser Diagnostic System (NIR seed laser)	*£ 200,000.00*	*£ 200,000.00*
Design (technical assistance) report 20k (WSP)	*£ 22,304.00*	*£ 26,764.80*
Total	***£ 537,680.00***	***£ 542,140.80***

Project Milestones, Actual vs Forecast

Shock Tube and Gas Mixing Facility

Task	*Forecast*	*Actual*
Market consultation	*June 2019*	*Jan 2021*
Specification development	*June 2019*	*Feb 2021*
1st Tender development	*July 2019*	*March 2021*
1st Tender period		*April 2021*
Second tender period via single source tender	*September 2019*	*June 2021*
Evaluation period/Contract award	*October 2019*	*Aug 2021*
Project Kick Off	*November 2019*	*Sep 2021*
Design Phase (including Outline design and detailed design)	*January 2020*	*Nov 2021*
Fabrication Phase	*August 2020*	*May 2022*
Delivery	*September 2020*	*May 2022*
Installation Phase	*October 2020*	*June 2022*
Commissioning Phase	*Feb 2021*	*June 2022*

Laser Diagnostic System (NIR seed laser)

Task	*Forecast*	*Actual*
Market consultation	*June 2019*	*Sep 2022*
Specification development	*June 2019*	*Dec 2020*
Tender development	*July 2019*	*Jan 2021*
Tender period	*September 2019*	*Feb 2021*
Evaluation period/Contract award	*October 2019*	*June 2021*
Project Kick Off	*November 2019*	*June 2021*
Design Phase (including Outline design and detailed design)	*January 2020*	*N/A*
Fabrication Phase	*August 2020*	*Mar 2022*
Delivery	*September 2020*	*April 2022*
Installation Phase	*October 2020*	*May 2022*
Commissioning Phase	*Feb 2021*	*June 2022*

Key Lessons Learnt

Shock Tube and Gas Mixing Facility

- Similar to previously identified lessons learnt with other equipment procurement activities, it is critical that the market research conducted before the tender is of high quality. These values were also pursued in this project. However, after a protracted period of research by the internal team it became clear that additional technical support was required to ensure the specification was suited to the market. Furthemore, it was understood from previous procurement attempts that an understanding of the marketplace with regards to potential vendors was also essential before releasing an invitation to tender. Hence, the project team employed WSP Ltd, a company familiar to the project team to produce an outline engineering design specification as well as a market assessment of potential vendors. This resulted in a high quality tender specification, which in turn resulted in three comprehensive bids. Unfortunately, none of these produced a suitable technical solution following evaluation. This highlights that even applying maximum due diligence to the exercise of open tender, procurement exercises remain a challenge. Project teams should consider this during the conceptual phase of the project. Whilst the objective of the project as a whole was to drive innovation, procuring technologies in this way can be a challenge, as companies would prefer shared risk design collaboration projects as opposed to direct turnkey design and build contracts. Often this is not considered an option due to the tight programme constraints of grant funding deadlines, however project teams should evaluate other procurement options at the concept phase.
- It is recognised that the extensive work in market research and design collaboration with WSP did result in links to the resultant principal contractor (Heblac Gmbh). A vendor that had previously produced similar systems and displayed a vast amount of experience in the area. However, by the time this relationship was established and an offer produced by the company, time remaining on the grant funding availability meant that the decision was made by the project team to proceed under single source tender outside the usual grant funding procurement regulations. I.e the project was entirely funded from within the University. This was deemed the only practical solution given the available time and resources available. Therefore the lesson here is that even with all of the best efforts to maximise the success of the tender if an issue arises or a tender exercise is not successful considerable pressure is applied to the programme. Therefore project teams must account for this potential when programming grant funded projects.

Laser Diagnostic System (NIR seed laser)

- The laser diagnostic tender and procurement process was a far smoother experience with this project due to elements of the design integration with the shock tube being resolved by WSP. Which in turn meant that the laser system could be bought from stock/off the shelf. However, the project team did benefit from an internal university expert in laser safety and systems, which enabled a strong specification to be produced, ultimately resulting in two competitive bids.

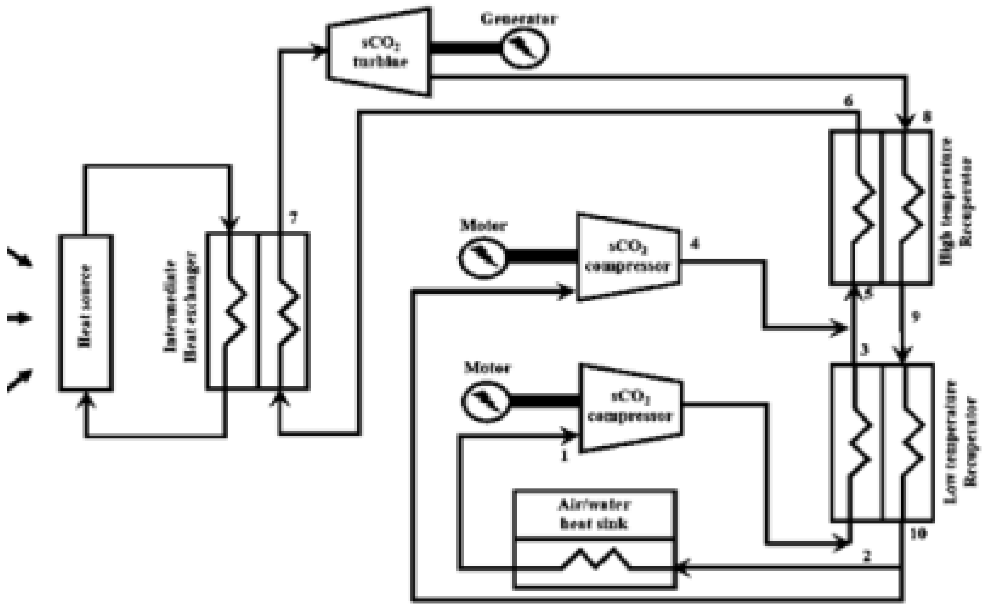
High Pressure High Temperature Heat Exchanger Test Bed (HEX Facility)

Original Project Design Intent

This reports the purchase of a high pressure, high temperature Heat Exchanger (HEX) test bed for high-efficiency power conversion cycles R&D, focusing on supercritical CO2 (sCO2) for oxy-fired gas cycles but also with global applications in other power (e.g. nuclear) and industrial sectors. The facility will enable the study of high efficiency heat exchangers covering areas such as heat transfer, pressure drop, thermal stresses, impact of phase changes, impurities, fouling, corrosion and materials research, including high temperature alloys and dynamic seals. It will provide performance data for the sCO2 cycle to model and evaluate designs, e.g. fluid passages.

In discussions with industry in the oxy-fired gas cycle area, TERC was identified as an ideal facility to establish a 30 bar 750oC test loop to support the RD&I programme of NET Power and its main UK collaborators: Heatric and Goodwin Steel Castings. In-system testing of advanced metallic heat exchangers and other system components will form the core of research activity, with cost reduction and enhanced performance as the priority areas. It is also likely that expertise from the AMRC would be deployed to assist with the development of both post-test materials inspection and analysis, and with production processes.

CO2 for the facility will be supplied primarily form the GMF. Product gases from the capture plants (MCFC, ACP and MP) may also be used. The facility will also be linked to the Methanation plant to provide high pressure CO2 for methane synthesis together with the hydrogen generated onsite from renewable electricity and electricity from other generating (CHP) rigs and the MCFC. The facility will also include a high pressure shock tube with analytical ports for fuels chemical kinetics research.



Final Project Design Outcome

The final High-Pressure Heat Exchanger test bed (also referred to as the HEX facility) which operates in the critical CO2 range achieved all of the original design intent outlined in the original grant funding agreement.

In principle the aim of the test bed is to evaluate the operation of a number of physically-similar heat exchangers of currently-unknown design, operating in turn in a back-to-back pair in the test bed. These exchangers will operate with streams of higher and lower pressure and high temperature supercritical carbon dioxide, containing various admixtures of other contaminating fluids likely to be found in a commercial power plant using CO2 as the working fluid (Allam cycle). These high- and low-pressure streams operate on both the heating and cooling sides of the exchangers, with the capability of having differing CO2 gas admixtures on the two sides of them.

The HPHE test bed is aimed at supporting R&D in high- efficiency power conversion cycles, focussing on supercritical CO2 (sCO2) for oxy-fired gas cycles (Allam cycle) but also with global applications in other power and industrial sectors.

The objective of the test bed is to establish a flexible test loop, ideally capable of operating at pressures up to 345 bar gauge/5000 psig, in support of R&D in oxy-fired gas cycles, but, in general, it is envisaged the facility will enable the study of high efficiency heat exchangers. This will cover areas such as heat transfer, pressure drop, thermal stresses and the impact of phase changes, impurities, fouling, corrosion and other areas of materials research. It will provide performance data for the sCO 2 cycle to model and evaluate new process designs, in particular for heat exchanger sizing. High-pressure heat exchangers such as those to be tested here will be used in a range of next generation low carbon technologies.

The HPHE testbed complements existing research capabilities for low carbon power generation technologies and applications in energy/CO 2 intensive industries. It is envisaged that the new HPHE test bed at TERC will provide an important platform to aid product (HPHE) development and innovation across a wide range of research activities. It is the intention that the HPHE test bed will be installed inside a standalone area with external connections to the supply of pressurised carbon dioxide and other trace fluids. Power and compressed air will also be connected to a utilities station on the west interior wall of the building, and all vent and safety valve emissions will be gathered to a central point above the HPHE and discharged to the atmosphere outside the TERC building through a dedicated vent duct.

Procurement and Legal Compliance

The rig was tendered via the full OJEU procurement process in accordance with Public Contract Regulations 2015. Furthermore, additional procurement regulations imposed by European Regional Development Fund, as a project partner, were complied with.

Principal Contractor Company Description, Financial Status and Background

Helical Energy Ltd (Helical) won the design and build contract to supply University of Sheffield (UoS) with a turnkey High Temperature High Pressure Heat Exchanger Testbed (HEX), for installation in the Translational Energy Research Centre (TERC).

Helical is the world's leading innovator of heat recovery systems for gas turbine exhausts and other waste gas streams, as well as combustion and gasification systems for biomass and waste fuels based on fluidised bed technology. They have also designed award-winning renewable energy power plants, including the detailed design of the fluid bed combustors, waste heat boilers, piping and electrical systems.

They boast the achievement of developing the most advanced offshore heat recovery boiler for 35MWe class gas turbines for a Norwegian energy major, as well as providing a solution for generating 900°C process gas for a leading business in the environmental industry.

History of Project Events

Following internal research of similar systems it was identified that additional external engineering support would be required to develop a suitable tender. A simple request for quotation for engineering design services to support with the development of the specification was released. WSP Ltd was identified as the most suitable company. They were contracted in October of 2019 and works commenced shortly thereafter. The University of Sheffield project team meets weekly to support WSP to develop the specification. In addition, WSP were also tasked with identifying suitable companies capable of developing a rig to the standard required. The report was delivered in May 2020 and included a detailed design specification. However, due to global events surrounding the pandemic at the time, WSP struggled to identify many suitable companies and the list of contractors supplied was relatively short.

The tender was released 14/07/2020 with a closure date of 21/08/2020. In total there were 11 expressions of interest. On the final day of the tender period, Strata Technology contacted the University to request an extension - a request that was denied due to the late request and the fact two submissions had already been submitted. Despite this Strata still submitted a bid resulting in three companies submitting a return.

The companies which submitted a bit were: Helical Engineering Ltd, Frazer-Nash Ltd and Strata Technology Ltd. Frazer-Nash did not submit a full tender, instead they offered their consultancy service, hence they were excluded from the evaluation. Strata Technology submitted a weak technical tender for a value of £1.99M. Helical submitted a comprehensive bid for £0.39M. The significant difference in valuation as well as the strength of the Helical technical bid resulted in Helical Energy scoring highest on the final evaluation.

Following evaluation, the mandated standstill period and a short contract negotiation period a contract was finalised by both parties on 4th September 2020.

The project design phase commenced immediately with a programme of technical workshops to develop the design. This initial technical documentation was issued in November of 2020. Following several months of further design it was identified the project would require a 93kW heater and associated ancillary equipment would be required. Whilst this is considered to be a relatively simple oversight, it was clear that this was not included in the tender. Therefore, the budget for the project was increased by £62,800 in February 2021. The design continued to progress and by April of 2021 the project design was ready for Hazop. In April 2022, the assessment was undertaken in collaboration with the University’s external safety and risk analysis consultants. The Hazop was performed over two days and was approved with only minor system changes required. However, this required several additional items of equipment to be added to the system. Following negotiation and discussion with Helical, the project team agreed to an increase of £18,450 in April of 2021. Design continued and in May of 2021 the design was approved.

Works commenced at the Helical headquarters fabricating the test rig in June 2021. The rig and its ancillaries were delivered in December of 2021. The initial installation and commissioning programme provided by Helical suggest the works would be completed within 3 weeks. However, the rig required integration with the building services including: specialist gases, electrical infrastructure ventilation and other similar areas. As such, an installation window of 3 weeks proved to be unrealistic. Ultimately with two technicians almost permanently on site, with additional contractors providing electrical and ventilation installation services, the installation took almost 3 months to complete.

At the time of producing this document (March 2022) installation was close to completion. A full commissioning and handover programme including insurance overwriting, hydro testing, electrical and mechanical testing, as well as hot and cold commissioning run days was provided. With a realistic forecasted completion date of April 30th 2022.

Project Budget, Actual vs Forecast

The project budget established at the grant funding stage was based on a combined budget for both High Pressure High Temperature Heat Exchanger Test Bed (HEX) and Shocktube system of £1,487,220.

Following design tenders and split down of the project the final project costs are as follows.

Item - *Heat Exchanger Test Bed (HEX)*	***Cost (Ex VAT)***	***Cost following application of appropriate VAT***
At tender	£ 390,750	£ 390,750
Contract Variation 1	*£ 62800*	*£ 62800*
Contract Variation 2	*£ 11,610*	*£ 11,610*
Final total cost	***£ 465,160***	***£ 465,160***

A fixed cost contract of £390,750 was issued under Purchase order XJ0 / 4501096952 on 04.09.2020. However, following several contract variations, the project concluded at £*465,160.*

Project Milestones, Actual vs Forecast

Task	*Forecast*	*Actual*
The research	*30/05/19*	*30/11/19*
specification development	*30/06/19*	*30/03/20*
Tender development	*30/08/19*	*22/05/20*
Tender period	*30/09/19*	*14/07/20*
Evaluation period	*30/10/19*	*04/09/20*
Project Kick Off	*30/10/19*	*04/09/20*
Design Phase	*30/12/19*	*05/06/21*
Fabrication Phase	*30/05/20*	*15/12/21*
Factory Acceptance	*30/06/20*	*30/04/22*
Installation Phase	*30/08/20*	*30/03/22*
Commissioning Phase	*30/11/20*	*30/04/22*

Key Lessons Learnt

- As identified with previous procurement exercises, the development of strong specification is essential. Therefore the project team's decision to procure engineering design support to develop the tender specification is considered to be a key factor in the success of this project. However, it is also recognised that despite this effort the tender only received one realistic bid. It is therefore difficult to predict the influence the enhanced specification had on the number of bidders, as it is always possible that it could have resulted in no bidders. But what is clear is that the design specification developed at tender stage heavily influenced and guided the eventual contractor with the design. Hence, whilst this additional step consumes time in the programme, in the long run this is absorbed in the design phase of this bespoke apparatus.
- The minimal number of bidders despite the significant number of 'expressions of interest' is disappointing. This could have been increased by extending the tender period. It is recognised that an extension request was received and denied at the tender of the tender period. The project team believes that granting the extension at this late stage would not have altered the outcome of the tender exercise. However, what is less clear is how successful the exercise would have been if the tender period was longer in the first instance as this may have enabled more of those companies that expressed interest in the tender to bid on the tender, when considering companies internal sign of processes.
- Despite the efforts pre-tender to develop the design and an extensive period of design, there were still a few oversights or elements of the specification that were not captured at the contract stage. This resulted in a circa 15% increase in the project budget. Fortunately the project team had sufficient funds to support this addition. However, it's clear that it is necessary to allow for a contingency even on complete design and build turnkey contracts.
- Despite the principle contractor being held to milestones by contract, it became clear early within the project that the supplier had been extremely ambitious with the programme for a completely custom research rig. Whilst the project team could have held a hard line with the contract during multiple stages of the project, including the design and installation phases, it was felt that this would not result in the successful delivery of the project. Especially during the pandemic, a host of challenges were present to both the supplier and the Sheffield project team. However, it is clear that it is the responsibility of the user/contracting party to take some responsibility for specifying realistic requirements in terms of cost, program and quality at the tender phase. Whilst all contracts put the responsibility for delivery of these project elements on the supplier at the delivery phase, the competitive nature of open tenders means that suppliers either deliberately or unconsciously err on the ambitious side in order to present the best scope to the customer. Hence in the future the Sheffield project team would advise that the scope is considered in any research phase and ideally that this would be independently assessed.

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