Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence

Tender Reference Number: 5045/04/2021

Lot 2

TWI Limited proposal PROP309232v1
Reviewed and signed off in accordance with TWI Limited policy.

1 Introduction

This proposal is TWI Limited's (TWI) submission in response to Lot 2 of Tender Reference Number: 5045/04/2021 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence'.

TWI is one of the world's foremost independent (not-for-profit) research and technology organisations (RTOs) with expertise in all aspects of materials joining, inspection and asset integrity management. TWI supports over 700 industrial member companies, who have activities on ~3,500 sites in 60 countries across all energy sectors. For decades, TWI has been the trusted independent advisor for qualification of materials that are critical to the safe transportation of hazardous media. We work across the end-to-end hydrogen economy value chain and have extensive facilities for:

- Materials characterisation;
- Mechanical testing of materials in aggressive environments (including hydrogen);
- Ageing and permeation testing of materials, and
- Determining the influence of materials and joining processes on joint integrity.

TWI has supported industry since 1946, and has historically supported a multi-sectoral client base. Its extensive activities in the energy sector has led to TWI to undertake significant activity over the past 75 years to understand how hydrogen affects the performance of materials, joints, assets and structures, and how to ensure their through-life integrity. TWI has undertaken millions of person hours of research to understand hydrogen embrittlement of engineering materials and how to mitigate against it. This includes the formulation of industry guidelines and the development of national and international standards.

Pertinent to this TWI has been involved in a series of state-of-the-art literature reviews and gap analyses, commissioned by TWI Members and potential suppliers to the UK and other nations gas transmission and distribution networks. The intention of this work was to determine whether existing gas transmission infrastructure can be operated with increasing partial pressures of hydrogen gas (i.e. in addition to natural gas), and to review the potential for deploying new infrastructure to enable increasing partial pressures of hydrogen gas. TWI has access to a significant materials testing facility, and research is being undertaken to address knowledge gaps in the above literature by conducting tests in our unique 'gaseous hydrogen' and 'permeation and ageing' laboratories, to establish the safe operating windows for various different materials, including those that are currently deployed.

Our position as a respected and independent R&D organisation makes us an ideally placed to engage with stakeholders on this topic, and to conduct independent third party reviews of the safety cases described in Phase I. Furthermore, our experience with the development of industry best practice guidance documents and our prior engagement with TWI Industrial Members on this topic, gives us the requisite experience to author best practice guidance documents.

As such, TWI is well placed to deliver Lot 2 of Tender Reference Number: 5045/04/2021 'Provision of Hydrogen End User Skills and Standards for Heat Supporting Research and Evidence'.

2 Objectives

3 Delivery Plan

3.1 Introduction

The work within this project will be undertaken in two stages in accordance with the tender requirements:

- Stage 1A: Literature Search and Assessment of Existing Evidence
- Stage 1B: Physical Testing

3.2 Stage 1a: Literature Search and Assessment of Existing Evidence

In order to establish whether the current low pressure end-user gas systems in both domestic and commercial buildings are suitable for conversion to hydrogen, a detailed literature review of domestic and internationally authored papers, articles and reports will be undertaken in-line with the tender requirements, in order to provide evidence on the suitability of currently used materials. The research will also determine how an individual could identify the materials that have been installed in a variety of settings.

This evidence will be assessed against identified criteria and defined as being:

- Fully relevant if the referenced material can be determined to be acceptable or unacceptable in a 100% hydrogen gas system;
- Partially relevant if there are specific attributes of the material that need to focused testing to determine its acceptability, or
- No relevant evidence if a full suite of testing needs to be undertaken to allow the required classification.

This review will allow a focused testing programme to be defined and undertaken in relation to the use of pure or blended hydrogen.

Relevant existing evidence will be interrogated, critically analysed, evaluated. TWI has access to scientific and technical literature in the public domain through academic research databases such as Scopus, ScienceDirect and Web of Science. It also abstracts from globally published literature, holding the world's largest database of literature in the field of joining and materials (Weldasearch®). Its dedicated information scientists are expert in interrogating the literature on behalf of industry and their expertise will be used to define search terms and establish available information. Further data will be drawn from the closed literature which TWI holds. This includes its internal research, performed through its Core Research Programme (CRP), which has published over 1,000 detailed technical reports. Recent examples include a review to understand the current state of the art in hydrogen transport, storage and service. Specific objectives of the review are to identify:

- Commonly used materials in hydrogen service;
- Operating conditions used in hydrogen service;
- Degradation mechanisms of polymeric materials, and
- Test methodologies for evaluation of polymeric materials performance.

TWI's experience with providing state-of-the-art reviews directly commissioned by industry gives it the necessary experience to ensure that the data gathered is accurate and reliable. This will ensure that the literature survey contains robust evidence which adds value to the Hydrogen Skills and Standards for Heat programme.

TWI will also work with Teesside University as a subcontractor on this task. Teesside is a hydrogen hub and Teesside University has supported industry within the region in the installation of hydrogen distribution systems. This work has included selection of materials based on performance, the data from which will be incorporated within this review.

TWI has undertaken commercial work in the field of testing materials in hydrogen. Some of the datasets generated are known to be available for inclusion within the review; other sponsors will be approached to establish whether their data can also be incorporated, with or without redaction.

TWI is a member of several standards organisations, serving on and also leading numerous committees. Through these links with e.g. the ISO (International Standards Organisation) and BSI (British Standards Institute) it will engage with the specific standards committees developing standard within BSI, IGEM (Institution of Gas Engineers & Managers) etc to verify understanding of the research questions. This engagement will continue through to the definition of the final test plan to ensure that the testing undertaken is of maximum benefit in closing knowledge gaps.

3.3 Stage 1B Physical Testing

Following on from Stage 1A above, physical testing will be performed to establish the specific properties of embrittlement and permeability in relation to materials defined through the literature survey to lack sufficient test data to establish their suitability or otherwise for application in a hydrogen environment.

3.3.1 Study Plan

A study plan will be developed and agreed to build on the evidence generated within the literature review. This will review whether there would be benefit in conducting tests to quantify the impact of hydrogen gas at velocity within piping systems, particularly at changes in direction. This assessment will factor in the implications of the increased velocity of hydrogen flow (3x that of natural gas). The study plan will define the method, experimental set-up and details (in-line with the facility details given below) and include analysis and conclusions from results to demonstrate which materials in common use in pipework, equipment and components for new and existing systems are suitable for use with hydrogen.

The materials for testing have initially been defined by BEIS. These include metals and polymers in common use within the domestic and commercial gas industry. The detailed methodology of the physical testing programme will be defined with reference to the tender requirements, including prioritisation of materials and test methods based on likelihood of materials being encountered and implications of failure. It is noted that a budgetary allowance for testing has been made within the programme based on anticipated needs through a provisional assessment of available data. The scope of this testing plan will be developed to fit within this budgetary allowance. In the event that the number of high priority materials identified where available data is insufficient and exceeds the available budget for testing, this will be discussed with the project reviewer to define priorities.

The overriding requirement is to demonstrate whether the performance of materials under hydrogen operation are different to the current assumptions for natural gas.

3.3.2 Basis of testing

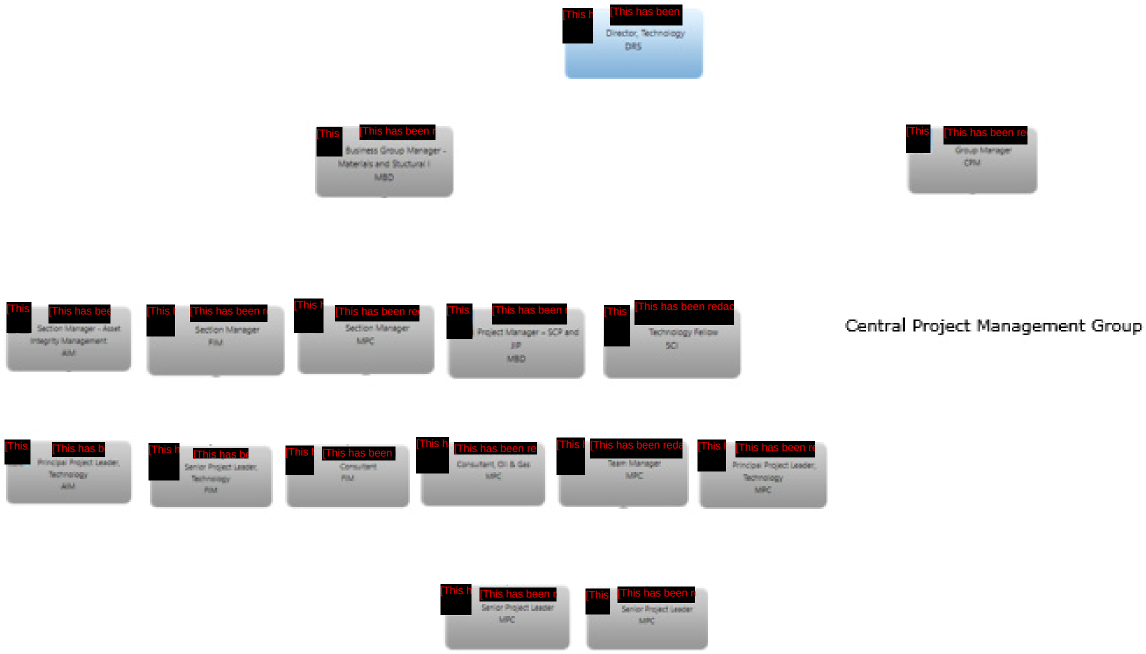
TWI confirms its proposed test programme will meet the basis of testing as defined within the tender document, ie pressure <75mbar, temperature range -30°C to +50°C in nominally pure hydrogen. Testing will be carried out using new materials currently available on the open market. Where relevant, samples from different manufacturers will be tested (most materials will need to be sectioned to provide suitable test specimens). Aged materials will be reclaimed from existing representative systems, based primarily on age rather than source. Materials will be tested at up to three sample ages for each material, subject to availability.

TWI is experienced in the delivery of projects which generate data that leads to the development of industrial standards. Its experience, set out below, in both the management of projects and in application of robust scientific method ensures that the data generated will be accurate and reliable, and thereby add value to the Hydrogen Skills and Standards for Heat programme.

TWI's background in handling hazardous environmental testing, including hydrogen up to 1000bar/1000°C (see full capability description below) provides the necessary experience to ensure that adequate safety and test procedures will be put in place to deliver this work.

4 TWI Capabilities

4.1 Organisational Chart



4.2 Relevant Staff

TWI has over 600 staff in the UK, with the vast majority of these having an engineering or scientific background. These backgrounds are particularly diverse with broad ranging expertise covering materials science, mechanical engineering, corrosion, manufacturing engineering, inspection and asset management. The relevant staff who will be involved in this activity are detailed below. The extent of their involvement will be dependent on the results of the literature review and the direction of the materials testing activity.

[redacted] is a Technology Fellow on Polymeric Materials and Aging through Permeation Processes at TWI, Cambridge. Permeation of H_2, H_2S, CH_4, CO_2, natural gas, water and hydrocarbon with resultant performance indicators all have developed methodologies. [redacted] has a wide range of experience in her previous role working in a series of satellites for Schlumberger developing specialist coatings that electrically insulate and elastomeric materials inc. wellbore sealants and polymer interactions.

[redacted] has worked at TWI, Cambridge since October 2000.
His current activities include managing a team of highly skilled engineers and consultants, delivering technical expertise across different industry sectors. He also oversees the development of PhD students within his Section of which he currently supervises three. He has extensive experience in fatigue of welded joints and is the Chairman of BS 7608 and WEE/37-3 as well as the UK national delegate for the International Institute of Welding (IIW) Commission XIII (Fatigue design).
He completed a PhD through the Open University under the supervision of [redacted]. The title of his research was [redacted]

[redacted]

[redacted] obtained her degree in Materials Science and Engineering from the University of Wales, University College Swansea in 1999 and joined TWI in the same year. She has been involved in research, materials selection and failure investigations, mainly with ferritic steels and has also supported engineering critical assessment activities by undertaking post-test metallographic assessment on fracture toughness test specimens. With her broad knowledge of ferritic steels with particular emphasis on hydrogen cracking and hydrogen diffusion, HAZ hardness, mooring chain, fasteners, in-service welding and 9% Ni steels, she has carried out numerous investigations in these areas including failure investigation as well as production qualification and research. She currently serves on several BSI committees, providing welding and metallurgy input to the standards as required, as well as lecture on the IIW/EWF diploma, providing training and mentoring in other areas of welding metallurgy specialisms.

[redacted] joined the Ferritic Steels section in TWI in 2004, conducting research, performing failure investigations and post-test metallographic assessment in support of engineering critical assessments (ECAs). During this time she has also had a significant role in developing TWI's high pressure hydrogen testing facilities as in 2007-8 she put together a business case, obtained funding for and organised commissioning of a new facility which allows mechanical testing to be carried out at pressures of up to 1000 bar of hydrogen. At the time, this facility was globally unique and [redacted] was awarded the WJS Richard Dolby Rolls-Royce Young Members' Prize for this work. [redacted] has continued to be interested in research and is currently working on materials properties in hydrogen environments.

[redacted] graduated with a Master's degree in Mechanical Engineering from the University of Leicester in 2010, after which he joined TWI Ltd. Focusing on a project called 'Mintweld', the aim of which was to develop numerical models to predict weld phenomena over multiple length scales. This led onto his PhD for which he wrote a thesis, entitled [redacted] furthering the understanding of hydrogen-assisted cracking mechanisms in dissimilar metal welds. [redacted] now works as a Principal Project Leader (Materials Engineer) at TWI, where his role involves managing confidential single-client projects and joint industry research programmes for TWI's members within the oil and gas, defence, aerospace, automotive, power generation and medical sectors.

[redacted] gained a B.Eng. from Iran University of Science and Technology in 2003 having specialised in metallurgy and materials science with emphasis on Industrial metallurgical processes, i.e. casting, welding, forming and physical and mechanical metallurgy. Whilst working at the University of Manchester he completed his Master's degree with a speciality in lightweight Materials (mostly Al, Mg and Ti alloys), and went on to complete a Ph.D. associated with metallurgy, metal forming and superplasticity of light alloys. [redacted] joined TWI in 2011 and is the Manager of the 'Materials Performance and Characterisation' Section. Throughout this time [redacted] has been intensively involved in managing and conducting single client and joint industrial and research projects with main areas of focus related to materials assessment/selection, microstructure property relationships, evaluation of resistance to environmentally-assisted cracking, particularly hydrogen embrittlement. This has been combined with expertise in service performance and failure including corrosion and fracture of metallic materials with particular interest in the quantified assessments of steels, nickel alloys, and their dissimilar metal welds subjected to hydrogen charging environments.

[redacted] joined TWI in December 2017 as a Project Leader within the Materials Group after graduating with a first class Master's Degree (MEng) in General Engineering from the University of Leicester in 2014. Whilst working at TWI she has completed a PhD investigating the elevated temperature performance of high strength steels (HSS) for structural fire design guidelines with Brunel University. The research included evaluating the material performance of different types of high strength steels at temperatures up to 900°C and relating this to the differences in the chemical composition and production route of the steels through material characterisation. [redacted] is responsible for the delivery of projects to a high level of technical quality within a desired time frame and budget. [redacted] has led several failure investigation projects related to ferrous components ranging from small components for automotive applications to large offshore structures. In addition, she has led and supported the material testing of alloys in extreme environments including elevated temperatures, high-pressure gaseous hydrogen and sour environments.

[redacted] is a Technology Fellow responsible for developing business, providing consultancy and managing projects for TWI membership companies. His experience covers fatigue design, fatigue life evaluation, engineering critical assessment (ECA) in accordance with BS 7910 and other international standards, fatigue testing and failure investigation. He has managed many projects since he joined TWI in 2001, including several joint industrial projects (JIPs) and has carried out a wide range of research activities with academics, as well as supervising PhD students. He has published about 70 papers in international journals and conferences, mostly as the principal investigator. [redacted] is experienced with a variety of methods and familiar with many international standards to characterise fatigue performance, his experience covering many corrosive environments including seawater, CO2, H2S, H2 and elevated temperatures.

[redacted] undertook her PhD on fatigue crack growth behaviour in a shot peened low pressure steam turbine blade material at the University of Southampton. After her PhD, she worked as a Research Associate in the Open University in characterization of electropulse induced microstructure regeneration of stainless steels. Then she worked as research engineer in the R&D centre of Vesuvius UK Ltd and then as research fellow in Brunel University, London. She joined TWI as a Senior Project Leader in 2018.

[redacted] has just completed her PhD from the London South Bank University, her thesis focusing on the testing and characterisation of durable super-repellent coatings undertaken as part of her tenure at the National Structural Integrity Reach Centre at TWI Cambridge. Before joining TWI as a project leader in 2020, [redacted] begun her journey in chemical engineering as a process engineering intern, before moving on to become an industrial trainee and process safety engineer challenger.

[redacted] has worked at TWI Cambridge since 1993. Previously he worked at the BP Chemicals Polymer Sciences Laboratories in Grangemouth, Scotland as a

Polymer Technologist. He is currently Technology Manager and Technology Fellow for Plastics, where he is responsible for co-ordinating TWI's R&D, consultancy, training and standards activities in this area. He is also a CSWIP-approved Plastics Welding Examiner. His main areas of expertise are in the welding, mechanical testing and NDT of polyethylene pipes, standards on plastics welding and the certification of plastics welding personnel. He also has a good knowledge of all of the other welding techniques for plastics. He has managed over 150 research and consultancy projects and has written over 30 technical papers, as well as organising a number of international conferences on plastics welding. [redacted] is the author of the [redacted]

[redacted] is a chartered mechanical engineer who spent ten years as a structural integrity expert with Frazer-Nash Consultancy and is now Section Manager for Asset Integrity Management at TWI. During his time at TWI Cambridge he undertook an engineering doctorate (EngD) at the University of Manchester, developing the understanding of fracture mechanics behaviours in complex configurations. [redacted] has significant experience in analysis of material performance and the demonstration of structural integrity of components in the power, petrochemical, and transport industries, through the use of complex computational analysis, defect tolerance and design code assessments.

[redacted] has worked at TWI Cambridge since 2000. Previously he worked at for TR Oil Services Ltd in Aberdeen from 1997 as a Corrosion Engineer. He was seconded to the Corrosion Awareness Campaign supported by BP, during which time he was in charge of planning and delivery of a campaign to support the corrosion management teams in reducing the total cost of corrosion. His current activities at TWI include managing research, testing, and failure investigations projects and leading integrity management projects for pressure systems operating in the oil, gas and petrochemical industries, power plants, steel manufacturing and structures; responsible to deliver the projects at high level of technical quality within the desired time frame and budget. He has extensive experience in both marketing and lecturing of the TWI damage mechanism courses and has carried out a wide range of research activities together with universities mainly on pipeline corrosion prediction, assessment and mitigation.

[redacted] returned to TWI Cambridge in 2021 as a Consultant for the Oil and Gas sectors after a period of time working for BP. He has brought with him a wealth of experience in relation to the subsea production of equipment and engineering solutions for hydrocarbon containment from his time as a Materials, Welding and Corrosion Team Leader and as the Chair of the DNV RP B204 Recommended Practise for Welding Subsea Equipment. It was during this time that he was also a Subject Matter Expert for International Oil and Gas Producers Association Standardisation.

4.3 TWI Facilities and Experience in Hydrogen Testing

As per the above schematic, the introduction of hydrogen into pipelines can lead to a series of observed consequences, from impact on short term mechanical properties to fatigue. The impact for particular materials can be observed through a combination of mechanical, environmental and permeation testing, combined with appropriate interpretation of the combined data.

4.3.1 Mechanical Testing

TWI has over 150 load frame available for mechanical testing of coupons and full-scale structures. Over 50 of these load frames are equipped with environmental chambers to allow mechanical testing of components in aggressive environments. This includes bespoke pressure vessels for mechanical testing of specimens exposed to pressurised hydrogen gas.

The maximum load and pressure range for this high pressure facility is between 50 - 100kN and 50 - 1000bar, with an operating temperature ranging from -50°C to +85°C. These machines can be used for tensile, fracture toughness, fatigue endurance and fatigue crack growth (FCG) testing. ASME B31.12 (2014) provides recommendations on design and use of components and pipelines exposed to hydrogen gas. The recommendations in that standard are mainly based on tensile testing data of plain steels. However, the work on welded joints is limited.
Regarding fracture toughness testing, it is recommended to conduct testing of notched specimens under either a constant load or displacement to determine the highest value of the stress intensity factor, KIH. It requires to hold the constant load/displacement for at least 1,000 hours. If this length of time is not available an alternative method, either by reducing the load hold duration or adopting the increasing load test method, could therefore be proposed.

4.3.1.1 Available Test Methods

The following mechanical tests could be conducted to evaluate the fracture and fatigue properties of alloys in different environments:

- Tensile testing in pure hydrogen, hydrogen-methane blends and pure methane (in the same hydrogen frame in all cases) - A facility to do this at low (below 200bar) pressure has recently been commissioned, enabling strain rates similar to those in ISO 6892.
- SSRT testing in pure hydrogen, hydrogen-methane blends and pure methane (at a 'standard' strain rate, in the same hydrogen frame in all cases).
- Constant displacement and load tests on notched specimens in hydrogen environment to determine the threshold stress intensity factor, KIH;
- Fracture toughness tests in air and hydrogen environments to determine J-R curves;
- Single specimen fracture toughness testing, in accordance with the DNV method, to determine load rate independent fracture toughness thresholds in hydrogen;
- Fatigue crack growth rate (FCGR) tests in air and hydrogen environment;
- Frequency scanning tests to determine the effect of loading frequency on FCGR in hydrogen environment;
- Tensile tests in air; and
- Charpy tests in air.

4.3.1.2 Evidence of Capability

As evidence of TWI's experience and activity in this area, the forthcoming paper, co-authored by TWI's [redacted], should be referred to. This will be presented at a special session of Technology for Future and Ageing Pipelines, 19-21st October 2021 in Ghent, Belgium.

Evaluation and risk assessment of materials for hydrogen transport

[redacted]
[redacted] Norway
[redacted] Cambridge, UK
[redacted] Norway
[redacted] Norway

ABSTRACT
[redacted] are considering using existing offshore natural gas transport pipelines for transport of hydrogen gas to the continent and UK. The paper is discussing effects of transporting hydrogen in C-Mn steel pipelines. Existing standards for hydrogen and natural gas pipelines have been reviewed related to materials properties, and gaps and risks have been identified. Preliminary results from fracture mechanics and endurance testing of base metal and girth welds for two existing natural gas pipeline steel grades in air and hydrogen have been presented and discussed. Conclusions and proposals for future work have been given.

4.3.2 Hydrogen Charging and Specimen Characterisation

TWI offers a wide-ranging materials analysis services, with specialists having in depth knowledge, surrounding material-hydrogen interactions, embrittlement, and pertinent degradation/damage mechanisms and failures. TWI has chemistry and metallography labs, and an advances electron microscopy suite, allowing a variety of detailed analysis to be undertaken.

4.3.2.1 Capabilities

Capabilities include:

- Hydrogen analysis (using hot and melt extraction methods, price per sample)
- Hydrogen analysis - carbon steels, diffusible hydrogen; total hydrogen or melt extraction (stainless steels or C-steels after completion of diffusible hydrogen test).
- Hydrogen charging in the split-tube furnace.
- Microstructural characterisation (pre- and post-testing, metallography and fractography (LM, SEM))
- Light microscopy - to include preparation, examination and photography; SEM of fracture faces, including examination and photography, and limited characterisation using EDX.

4.3.3 Permeation Testing

TWI has a facility that allows the permeated fluxes of hydrogen through non metallic materials to be measured using the continuous nitrogen sweep method supported by specialist gas chromatographs. This method is non standardised but is a well established scientific method. Specimens are often discs cut from pipe sections. In follow on projects, pipe sections with lengths of 9ft can be assessed. At present the lower temperature range of testing is 22°C and 1barg. It is recommended that 3 temperatures are chosen in the range to 50°C at pressure of 14psig or 971mbar. Once the activation for permeation is known, then transport coefficients can be extrapolated to -30°C, in principle assuming the Tg is not in that interval. The experiments will be done in duplicate with two materials allowed for.

4.3.4 Asset integrity assessment and data interpretation

TWI are expert in the demonstration of structural integrity and suitable materials performance for components in high integrity components. We use deterministic and risk-based assessments, supported by numerical modelling, data analytics and methods and algorithm development to construct rigorous integrity arguments, providing assurance that equipment is safe, productive and profitable for its lifetime (and beyond).

We can therefore support this program through our general mechanical engineering, damage mechanism and materials performance knowledge, contribute towards the analysis, interpretation and manipulation of material datasets, as well as provide project management support and technical report writing capability.

4.3.5 Project Leverage - Current Core Research Projects

As detailed *above, TWI undertakes an internally funded Core Research Programme (CRP), worth ~£3.5million per year. There are several on-going CRP projects related to the hydrogen economy, whose results may be leveraged for this project. Activities being undertaken include:*

- *A review to understand the current state of the art in hydrogen transport, storage and service. Specifically to identify:*
    - *commonly used materials in hydrogen service;*
    - *operation conditions used in hydrogen service;*
    - *degradation mechanisms of polymeric material, ands*
    - *current test methodologies for evaluation of polymeric materials performance.*
- *Hydrogen exposure – The effect of exposure to hydrogen at high pressures and the effect of hydrogen diffusion on the micro- and macro-structure of selected materials.*

- *Accelerated weathering – The effect of UV radiation on the degradation of thermoplastics is well known, however how this may impact further on the physical properties is less well known. Effects such as colour change, loss of gloss, polymer degradation and weight loss are all mechanisms that may contribute to a reduction in their overall physical and mechanical properties.*

- *Thermal cycling – Low temperatures (down to -70°C) can increase the risk of failures of polymers due to embrittlement; high temperatures (up to 120°C) can increase the risk of failure due to polymer degradation. Cycling between the two extremes of temperatures may be sufficient to induce stress cracking into the polymer. Cracking and embrittlement can cause areas for moisture ingress, especially at enhanced levels of humidity (up to 98% RH), and the associated degradation that follows thermal cycling.*

- *Combined cyclic testing – Focused qualitative and quantitative testing via visual and physical methods will provide valuable data as to the performance of polymers in hydrogen service, and the combined test method will gain a more accurate insight into the cumulative effects of heat, temperature, humidity, etc. on thermoplastics and their physical and mechanical properties.*

5 Deliverables

The following will be delivered to the BEIS Heat programme as outputs from the project:

- Literature review, by 14th January 2022.
- Test Plan, delivery and approval of the test plan by 14th February 2022.
- Written report including all data, both raw and processed will be provided by 14th February 2023.
- Project presentation (assumed by teleconference or at TWI Cambridge) summarising results to project stakeholders by 14th February 2023.

These dates are based on a contract start on the 15th November 2021. The project completion date will be 14th February 2023.

6 Summary of Pricing

Task	Price - £k
Literature Review	[redacted] (inc. [redacted] subcontracted to Teesside University)
Development of Test Plan	[redacted]
Testing (total budget)	Up to [redacted]
Testing breakdown per test/material/condition - Permeation 1- Tensile testing in pure hydrogen, hydrogen-methane blends and pure methane 2- SSRT testing in pure hydrogen, hydrogen-methane blends and pure methane at a 'standard' strain rate testing with gas mixes (see above), but would anticipate approximately [redacted] per test, 3- Hydrogen analysis (using hot and melt extraction methods) Hydrogen analysis - carbon steels, diffusible hydrogen total hydrogen or melt extraction (stainless steels or C-steels after completion of diffusible hydrogen test) 4- Hydrogen charging in the split-tube furnace	12 experiments will cost [redacted] and can be pro-rated down to [redacted] for a pair [redacted] specimen [redacted] specimen [redacted] specimen [redacted] triplicate test [redacted] sample [redacted] for the first charging run (unless there is a requirement for long duration charging), [redacted] for subsequent charging runs.

5- Hydrogen diffusion simulation for a 1-D diffusion simulation 6- Microstructural characterisation (pre- and post-testing, metallography and fractography (LM, SEM)) Light microscopy, to include preparation, examination and photography (assume specimen size below 40mm in cross section) SEM of fracture faces, including examination and photography, and limited characterisation using EDX, if required - Specimen dimensions assumed to be 50mm cube. Machining	[redacted] per simulation [redacted] specimen [redacted] specimen [redacted] (assuming surface finish is normal engineering machined or extruded finish)

7 Timeframe

TWI acknowledges the timeframe for delivery required within the invitation to tender and confirms that the programme is scheduled to meet this. Key dates are contract start on the 15th November 2021, delivery of the literature survey (1A) by 14th January 2022, delivery and approval of the test plan by 14th February 2022 and completion of the project by 14th February 2023, total duration 15 months.

8 Milestones

TWI acknowledges the key milestones as stated in the invitation to tender, specifically:

Ref.	Expected Milestone	Percentage Paid
1	BEIS acceptance of the project delivery plan	0%
2	BEIS acceptance of literature review	10%
3	Interim presentation and report of progress (to be held and submitted once at least 50% of the work can be presented)	30%
4	BEIS acceptance of the draft report	30%
5	Receipt of final report	20%
6	BEIS acceptance of the final report	10%

and hereby confirms acceptance of the payment schedule.

9 Commencement, Communication and Project Management/Quality Assurance

9.1 Project commencement

After receipt of Order and review of commercial terms, TWI will review the technical scope and resourcing requirements. The project start date and duration will be reviewed based on the availability of equipment, and human resources.

A kick off discussion will be arranged to initiate the project. The Client should advise TWI as soon as possible should their delivery timescale for material, information or equipment supply differ from that stated in this proposal.

9.2 Communication plan

Communications planned within the project are as follows:

- Project inception meeting including a presentation of the project plan
- Progress updates (monthly, with additional meetings around milestone deliverables)
- Monthly report as a written summary by email, including:
  - a general overview of progress and KPIs, supported by the relevant reports as required;
  - progress against the timetable, where delays are anticipated or reported, an explanation for these and a proposed plan for resolving the causes will be presented;
  - challenges and risks;
  - requests to the BEIS project team for additional input from other parts of the Hydrogen Skills and Standard for Heat programme.
- Quarterly report on evaluation KPIs scored green, amber and red.
- Interim meeting presentation
- Interim project report
- Final presentation

A contract variation may be required to respond to requests that arise during review meetings, discussions or email exchanges. Contracts may be amended or modified in whole or in part at any time by an agreement in writing by TWI and the Client in accordance with TWI's Change Management procedure (below). Such changes cannot be agreed verbally, or via informal email exchange.

9.3 Project Manager and Quality Plan

TWI manages all projects using a framework closely aligned to the PRINCE2 project management methodology, tailored to suit the individual needs of each project, the project management structure with associated risk management forming the quality assurance plan. A Central Project Management (CPM) team acts as a Project Management Office (PMO) providing professional project management support to projects of significant size or those involving key clients. CPM employs a team of experienced project management professionals who are both qualified PRINCE2 practitioners and Association for Project Management (APM) qualified Project Managers. The CPM team will support this project. [redacted] Director responsible for Quality will validate quality assurance through a dotted reporting line to [redacted] who oversees project management at the group level supported by CPM

TWI will assign an experienced Project Leader/Co-ordinator to manage the project, who will maintain close contact with the Client throughout the work programme. All work will be carried out to a high standard and reasonable efforts will be made to achieve the project objectives. The project manager will be responsible for delivery of the management plan.

Applying the PRINCE2 and APM principles to this project will ensure that the project is delivered in a disciplined and controlled manner. TWI will hold regular internal project reviews during which the following will be reviewed and updated as required:

- Progress against the project schedule.
- Progress with contractual deliverables.
- The project risk register.
- Allocation of specific work packages to project team members with clear specifications and target dates for completion.
- Highlight reports from internal project members.
- Actions against project members that are recorded and tracked using an action tracker highlighting red, amber, green actions to identify priority and timescale for completion.
- Requirements placed upon suppliers to comply with the requirements of the contract.
- Project specification, scope, schedule and cost.

This management approach will ensure delivery of the project on time and on budget against scope.

9.4 Management of Sub-Contractor

TWI will make use of the specific insight of Teesside University via a subcontract. The subcontract accounts for 10% of the tendered activity and has been quoted against a clear and defined scope with staged payments against delivery. The project manager will ensure delivery is in line with scope, for both time and cost, to ensure value for money and overall impact is achieved in line with the project plan.

9.5 Risk management

Prior to commencement of any work, a structured risk review will be conducted. Each risk is assessed on the basis of its likely impact upon cost, performance and schedule and assigned a score based upon probability, impact and proximity. Mitigating actions are determined and recorded in a risk register and reviewed as part of every project review throughout the duration of the Contract.

Risks currently foreseen:

- Material supply: availability of materials in all desired conditions (aging). Mitigated by access to TWI's industrial network for supply of parts and through engagement with the broader **Hydrogen Skills and Standards for Heat team.**

- Resource availability: heavily utilised equipment, staff availability due to further COVID restrictions. Mitigated by scheduling provisional equipment bookings on receipt of notification of project award and by availability of duplicate cover in most skills. TWI has remained open for business in full throughout the pandemic and with the effectiveness of measures in reducing pressure on key infrastructure, does not anticipate tighter restrictions in future.
- Project management: uses resources in multiple teams across the business, mitigated use of project management tools to schedule resourcing.

9.6 Decisions

A stage gate approach will be applied. Meetings will be held between TWI and the Client to agree on next steps on completion of tasks. It is assumed that this review will take place within two weeks of completion of the literature review and the test plan, and a further week has been allowed for confirmation of the preferred route forward. Any delay will invalidate the project duration quoted in this proposal and any previously agreed delivery dates. TWI will notify the Client of a revised duration and/or delivery date upon confirmation of plan.

The completion of each task constitutes a project hold point and the stated project duration assumes authorisation to proceed is received within two weeks. Any delay will invalidate the project duration quoted in this proposal and any previously agreed delivery dates. TWI will notify the Client of a revised duration and/or delivery date upon receipt of material.

9.7 Change management

TWI has an internal process for managing change in projects. This is to ensure a robust and auditable process covering changes during the execution of the project and that a clear audit trail of submission, impact assessment and acceptance of change is recorded.

Any changes from what is stated in this proposal, including but not limited to, price, work scope, quantities or quality requirements must be formally recorded and agreed in writing by both parties. Such changes may necessitate a modification of the original prices or durations as specified in this proposal. This may be documented by TWI in a change control note (CCN) document, or an equivalent format as may be requested by the Client. The CCN document or equivalent format will require the mutual agreement of both parties and must be supported by the issuance of a commercially valid purchase order before implementation of the approved changes will be effected. For the avoidance of doubt, TWI will not affect any changes howsoever arising from what is expressly stated in this proposal. This may therefore result in the project or affected tasks being put on hold where applicable until TWI has duly accepted a commercially valid purchase order covering the requested changes.

9.8 Health and safety

Visitors to TWI are required to comply with TWI health, safety and personal security requirements when on TWI premises.

TWI requires the submission of all health, safety and personal security requirements for TWI personnel who will be visiting Client premises or working on site. Mobilisation of staff to site will not proceed until adequate health, safety and security arrangements are confirmed to be in place.

TWI is adopting all UK government recommended measures to minimise the risk posed by COVID-19 to both its customers and its employees. Work on any site outside TWI will not be committed to until TWI is satisfied that the safety arrangements meet the standards required for the UK workforce, including measures to safeguard staff during the COVID-19 pandemic. A full risk assessment will be undertaken at time of order placement, and will be reviewed immediately before mobilisation and when UK government guidelines change.

10 Social Value

With the growing demand for a 'greener' fuel, the emphasis on the environmental benefits of the use of hydrogen has grown exponentially. This in turn will leave a legacy of improvements in relation to the national energy network that will impact not just the individuals, but also communities and society. This fundamentally enabling step is critical to addressing climate change by enabling the UK to meet its 2050 net-zero targets in order to leave a sustainable legacy for future generations.

As can be seen from the diverse members of the project team, TWI recognises and values diversity within its workforce. TWI actively encourages an inclusive approach, apparent in the staff biographies above, exemplified in the breadth of opportunities that staff have chosen to follow. TWI has initiated and supported The Tipper Group in order to encourage growth of representation in engineering across all groups within society and specifically supports the development of engineers entering the profession through the Younger Members Group of the Institute of Welding and Joining. As referenced in the risk mitigation, it is the breadth of TWI's capability and its ability to utilise that expertise across the Team, that which creates and maintains a robust and resilient capability within the organisation. The opportunities presented by this project to disseminate the data generated also enable TWI to support the development of a more diverse workforce within the gas distribution sector as a whole.