AEROSPACE TECHNOLOGY INSTITUTE

Hydrogen Capability Network

Hydrogen Innovation Initiative

Cryogenic Hydrogen Materials Research Workshop Summary

August 2024

Contents

The ATI creates the technology strategy for the UK aerospace sector and funds world-class research and development. Hydrogen Capability Network acts on key recommendations from FlyZero to become an essential enabler of UK technology development.

Executive Summary

The move to liquid hydrogen as a fuel source, as recommended by the Aerospace Technology Institute's (ATI) FlyZero project, will be the biggest disruptor to the aerospace technology landscape since the introduction of the gas turbine. To meet the ambitious entry into service dates set by airframers the transition to liquid hydrogen will require significant and rapid development of new technologies. A hydrogen fuel storage and delivery system will require a greater depth of knowledge of the behaviour and impacts of cryogenic hydrogen than is currently present within industry or academia within the UK.

The ATI's Hydrogen Capability Network (HCN) has identified a priority need to bolster fundamental and pre-normative research in the UK to support liquid hydrogen fuel systems technology development with a primary focus on:

- Cryogenic hydrogen thermofluids behaviour
- Fundamental material behaviour at cryogenic temperatures and hydrogen environments
- Cryogenic hydrogen health and safety protocols, modelling, and testing

The HCN are now working to develop collaborative strategic research projects on these topics, considering the international landscape and industrial priorities.

This report details the outcomes from a workshop on hydrogen materials challenges and potential solutions. The workshop had 26 attendees from 22 organisations, including industry, research organisations, and academia.

The workshop concluded that the fundamental science behind low temperature and hydrogen effects on materials, including thermal, mechanical and chemical effects, both with gradients and cycling, needs research, considering experimental and modelling. The focus of this work should be on structural materials, primarily metallics, and it should consider sealing materials and the effects of joints and points of integration (welding, bonding, etc.). These reflect the opinions of those who attended the workshop and are not intended to be viewed as developed proposals for action, nor exhaustive.

Over the next 6 months the HCN will build on these requirements to determine the best route to addressing the research challenges that exist for the aerospace sector to be successful in technology development. Developing a challenge-based approach and as appropriate collaborative strategic research projects to enable industrial R&D.

Introduction

The FlyZero project developed roadmaps covering the technologies needed for liquid hydrogen (LH2) flight to be viable[1]. These cover topics that are both generic (such as automation and digital twins) and specific (such as aerodynamic modifications to manage dry wings, fuel cell development and gas turbine hydrogen combustion), as illustrated in Figure 1. In work carried out by the Hydrogen Capability Network (HCN), involving engagement with key stakeholders, it has been demonstrated that the UK has strong existing knowledge and research capability in many of the topics required to deliver an aircraft capable of liquid-hydrogen-powered flight. There is, however, a clear exception with on-aircraft cryogenic hydrogen fuel storage and delivery systems. Thus, intervening to accelerate the development of fundamental knowledge and capability in this area within the UK will enhance the UK's ability to contribute to the development of zero carbon aircraft. This aligns directly with both Government's Net-Zero policy objectives and the objectives of the HCN.

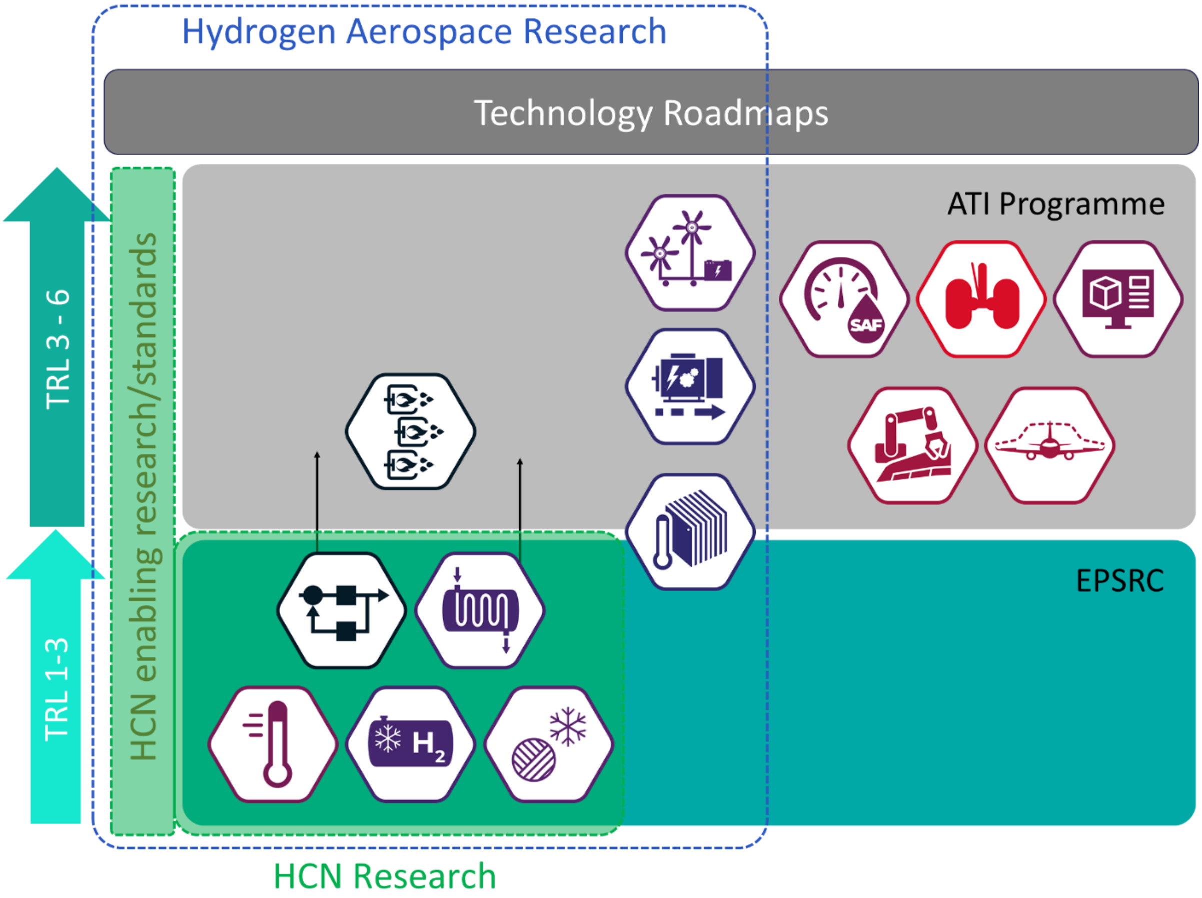

Figure 1 Technologies in which development is required to deliver LH2 powered flight

The challenge relates specifically to the storage and movement of hydrogen fuel between the fuel tanks and power source across a large range of fluid temperatures and pressures. Key research areas include the management of fluid phase transition from liquid to gaseous states in a controlled manner to ensure component function and life; the impact of hydrogen on the component integrity; and how to sense and manage hydrogen leaks safely, particularly in flight. While the requirements have initially been driven by aerospace, there is relevance to other sectors that have plans for the use of liquid

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[1] FlyZero Reports Archive - Aerospace Technology Institute (ati.org.uk)

hydrogen in the future, and a link to these requirements is being maintained through the Hydrogen Innovation Initiative (HII)[2].

During the first 12 months of the HCN, the following topics were identified as requiring particular focus:

- Cryogenic hydrogen thermofluids behaviour
- Multiphysics understanding of materials at cryogenic temperatures
- Cryogenic hydrogen health and safety protocols, modelling, and testing

Now the HCN is further developing these topics into research proposals, and this report captures the outcome from a workshop focussed on the challenges and potential solutions for hydrogen materials held on 25th March 2024. The workshop was attended by 26 people from 22 organisations, including industry, research organisations, and universities, as listed in Appendix 1.

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[2] Home - Hydrogen Innovation Initiative

Summary of challenges

Approach: the workshop participants were first placed in breakout groups with a mix of academic and industrial backgrounds and asked to develop a list of the key challenges and issues in the field of fundamental materials behaviour that need to be overcome to realise LH2 flight. The discussions from all the breakout groups were then collated into a list of key topics that were agreed amongst all participants.

The key topics are below and a summary of the broader discussions in each area is presented in the following sections.

- Material systems – identifying, understanding, and developing material systems of interest.
- Experimental testing – identifying and understanding the impact of the operating environment and developing suitable test and measurement techniques and hardware.
- Skills and knowledge transfer – ensuring that learning is shared throughout the community.
- Simulation – developing and validating modelling techniques.

Across these main topics there are some overarching questions around the key roles of materials in LH2 aerospace fuel systems and which properties are important in different applications. Examples of these roles include sealing and load carrying, both of which have different important material requirements. For specific materials that have been identified as being of interest for each application, awareness of which key properties are affected by hydrogen and cryogenic environments across the entire LH2 aerospace fuel systems operating envelope is important. Developing an understanding of the mechanisms which cause these identified material behavioural changes is also needed.

Hydrogen transport in all materials must be understood, both for leakage and its potential impact on material properties. Transport should consider both the movement of hydrogen into the material and the movement of hydrogen within the bulk structure. For this, an understanding of the effect of temperature, pressure, isomer, and purity of the hydrogen needs to be considered alongside the effect of stress state and surface conditions (oxides, coatings etc.) for each material. Molecular effects including surface interactions also needs to be investigated alongside the impact of the materials bulk composition structure.

Once hydrogen has been absorbed into the material, the effect of any absorbed hydrogen alongside the effect of temperature must be considered on its properties.

Material

A wide range of material should be evaluated for suitability across a range of different applications in cryogenic hydrogen environments.

Structural materials of interest include both a range of metals and fibre reinforced polymer composites. Metals of interest include stainless steels, aluminium alloys, and nickel alloys; both glass and carbon fibre polymer composites were discussed. Metals are seen as the nearer term, more mature solution with key questions around hydrogen embrittlement. The key challenge raised for composite systems was more around the low temperature effects, particularly in the understanding of the impact of mismatched coefficients of thermal expansion between resin and fibre systems.

Performance and suitability of sealing materials should also be evaluated at cryogenic temperatures, with a key point raised about the move to fluorine-free sealing materials. The evaluation of coating performance regarding durability and hydrogen diffusivity in a cryogenic environment was also discussed, as too was the evaluation of insulation, lubricant, and electrical materials.

There was consensus that evaluation should initially focus on greater understanding of materials currently used in cryogenic and hydrogen environments, with a future scope that could include new materials discovery. Concerns were raised around the current use of more industrial grade materials in existing cryogenic systems, due to the wide tolerances in these material formulation specifications. The potential variation in material behaviour and properties when at the outer ranges of the materials formulation specifications could lead to the use of highly conservative material properties for aerospace product design and reduce optimisation in aerospace applications, highlighting a potential need for tighter materials specification tolerances.

The impact of processing, manufacturing, and joining materials was also highlighted as a key area of interest to understand their impact on the materials performance.

The complete list of topics discussed and considered by the workshop is summarised as:

- Structural Materials
- Metals
- Polymers
- Composites
- Sealing Materials
- New Discovery
- Multifunctional
- Coatings
- Joints / Points of Integration
- As Built

Experimental testing

Development of both the understanding of how to carry out materials testing for LH2 applications and the development of the equipment and capability available for testing is required.

The standardisation of material property test methods at cryogenic temperatures and in LH2 environments is being investigated in the HCN’s CHYMES (Cryogenic Hydrogen Materials Test Standards) proposed project.

At material coupon level, experimental methods need to be developed to understand the fundamental mechanisms for material performance and degradation in cryogenic hydrogen environments. To do this, test parameters of temperature and cooling rates, hydrogen pressure and exposure time, loading rates and cyclic conditions need to be defined and linked to aerospace applications, and an understanding of their impact developed. Unless the effect of variables can be isolated, test apparatuses may need to be capable of providing variable strain rates, multi-axial stress states, and/or cyclic loading simultaneously with variations in temperature down to 20K and in hydrogen environments.

Industry expressed specific concern in the current ability to evaluate the life of components. Apparatuses for accelerated aging evaluations must be developed specifically to enable the long-term exposure of specimens to LH2 alongside cyclic thermo-mechanical loading over an extended period. Understanding of a methodology to distinguish design for safe life verses fail-safe within context of aerospace components at cryogenic temperatures needs to be developed, alongside potential methods for non-destructive evaluation.

Apparatus for the evaluation of thermo-physical properties and tribology is also required across the cryogenic temperature range and may need also to include the impact of hydrogen exposure together with temperature effects. More specialist apparatuses to understand magnetic and electrical properties in a cryogenic hydrogen environment may also be required.

Experimental techniques for investigating hydrogen transport and trapping mechanisms at low temperatures are also required, including quantification of hydrogen adsorption, ingress, egress, and distribution of hydrogen. Activity is also required to understand the impact of the hydrogen charging and loading methodology, comparing ex-situ electrochemical and in-situ autoclave conditioning, and their reproducibility and representation of real-life scenarios.

Transport measurement is required both in unstressed and stressed coupons to understand the impact of hydrogen movement at stress concentrations such as crack tips. This experimental capability would allow the evaluation of impact of temperature, pressure, and stress-state on hydrogen transport to further understand the mechanisms driving adsorption and diffusion. An understanding needs to be developed of hydrogen distribution in relation to microstructure and impact on fracture, fatigue, and degradation mechanisms, as well as impact of temperature and hydrogen on phase stability.

The material property measurement should be supported by analytical capability to evaluate characteristics such as microstructure, residual stress, and damage initiation and growth. Only with the combination of these test and analytical capabilities can the interdependent mechanisms driving mechanical thermo-physical and hydrogen transport properties be understood.

Beyond bulk material properties, specimen design would also allow the determination of the impact of thermal history, material processing route, and joining methodologies. Test specimens may need to be developed for evaluation of joining methods compatible with the geometric limitations provided by cryostats.

To carry out this testing, sensing technology for mechanical and thermal analysis must developed and verified to operate at 20K and in H2 environments. This includes sensors to indicate the phase composition of hydrogen (para to ortho) to understand how material behaviours vary with H2 phase composition and to identify any catalytic effects of materials on the phase composition. Precise control systems will be needed to maintain temperatures at 20K and an understanding of localised heating due to deformation will be required. An evaluation of the applicability of proxy fluids, such as liquid helium, to evaluate the discussed properties would also be beneficial to simplify test rig and facility design, owing to less restrictive health and safety implications.

The complete list of topics discussed and considered by the workshop is summarised as:

- Test parameters and requirements
- Cross comparing techniques and standardisation
- Charging/loading method
- Transport measurement
- Long-term aging
- Tribology
- Sensing technology
- Non-destructive testing

- Volume of hydrogen required
- Specimen condition - stress and mechanical history
- Environment
- Pressures and temperatures for H2
- State / Condition of hydrogen and quantity
- Manufacturing as built
- Thermal history
- Thermomechanical cycles
- Time
- LH2 vs LHe
- Lifing
- Cycling (thermal and load)

Skills and knowledge sharing

For the most effective development of fundamental research and roll-out of capability, skills development is required across multiple roles related to laboratory activities, including technicians, engineers, and health and safety personnel.

Given the very limited knowledge and experience in physical testing with LH2, sharing of knowledge is key to enabling fast and efficient development, and combining expertise with adjacent sectors such as the low temperature physics community and oil and gas industry could significantly accelerate progress.

Sharing of best practise will be required within the community, particularly regarding the safety concerns of working with cryogenic and combustible fluids. The limited current understanding and use of LH2 means good practice documentation would be highly beneficial.

Challenges in the supply of LH2 for experimental facilities could hold back the research and support that is required in the development of business cases for this capability and in the supply of LH2 for the quantities required in materials laboratories. Guidance across methodologies for on-site liquefaction technology and LH2 delivery would be beneficial.

Alongside the UK community, work should take place to engage with the international community to augment and benchmark test capability.

Interest was expressed in a testing centre of excellence with co-ordinated and open access facilities, along with an open access materials database that provides data across the full range of material properties.

The complete list of topics discussed and considered by the workshop is summarised as:

- Cross sector
- Experimental and simulation integration
- Co-ordination
- Theoretical and practical
- Data sharing
- Gap analysis, landscape analysis, and benchmarking

Simulation capability

Due to the high costs and practical challenges of working with LH2, the development of experimental test capability could be coupled with the development of simulation capability for greater efficiency. Simulation could be used to drive understanding of fundamental material behaviour at an effective rate, with validation coming from experimental test capabilities.

Modelling should be used to evaluate material degradation mechanisms, both those from low temperature and hydrogen exposure. The modelling also needs to reflect the combined effects of these across the range of relevant temperatures and pressures.

Hydrogen transport models would also be of value, considering the interdependence of temperature, pressure, mechanical stress fields, and hydrogen transport and distribution in a fully coupled model, incorporating microstructural features.

These requirements drive multi-physics and multi-scale modelling capability, allowing understanding of mechanisms acting across nano to micro scales. The bridging of scales in a cost and time effective way is a current challenge.

Understanding of hydrogen diffusion, deformation, fracture, and fatigue mechanisms, including under multi-axis loading, needs validation through modelling and experimentation. Additionally, current modelling capability must be validated by experimentation to demonstrate applicability across temperature range of the fuel system. Error estimation of models should be available and traceable. Access to high powered computing (HPC) could be useful but was not expressed as a key priority.

The complete list of topics discussed and considered by the workshop is summarised as:

- Multi-scale and multi-physics
- Validation
- Error estimation and management
- Uncertainty quantification
- Meso scale techniques development
- Degradation mechanisms
- Access to HPC

Challenge prioritisation

Approach: the workshop participants were asked to vote on the challenges highlighted to provide a technical prioritisation. Each participant received ten dots to indicate their highest priority challenges. The sums of these votes are provided in Figure 2, also indicating the different views or priorities of industry to research organisations.

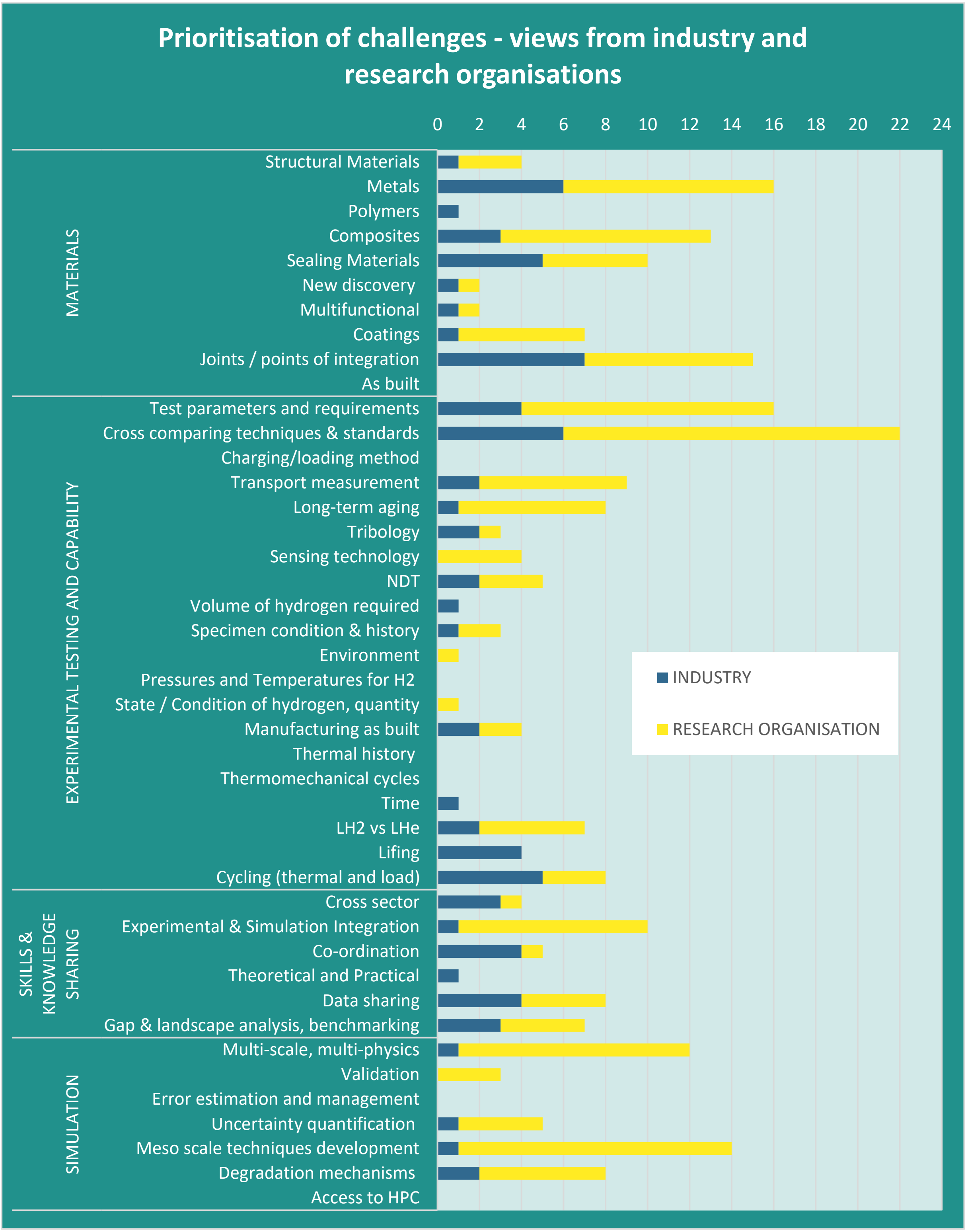

Figure 2: Prioritisation of Challenges

From the discussion above and the prioritisation shown in Figure 2, a research programme to establish the fundamental science behind low temperature and hydrogen effects on materials should consider the impact of thermal, mechanical, and chemical conditions, including impacts of gradient and cyclic effects. Research is required through experimental and modelling methods and will be most effective with co-ordinated activity between the two approaches. Both industry and academia prioritised the evaluation of metallic structural materials, sealing materials, and the effect of joints and points of integration. Modelling capability must be capable of multi-physics and bridge from nano- to meso-scale effects. Development of standardised testing techniques was also highlighted as a key challenge; an activity already being addressed by HCN's activity in the CHYMES project.

Addressing these challenges

Approach: the workshop participants were asked to provide their view as to how these challenges may be addressed through research and comments raised in the workshop are described in the below table. These reflect the opinions of those who attended the workshop and are not intended to be viewed as developed proposals for action, nor exhaustive.

Challenge area	Proposed activity
Material	• Prioritisation of materials of interest from industry • Collation of existing materials data, initially focussed on mechanical, permeability, and phase transformation data • Structural materials (steels and aluminium) • Fibre reinforced composite materials • Joints – adhesives, welds, and other methods • Seals – metallic and elastomers • Coatings – including performance as permeation barrier and evaluation of integrity through thermal cycling • Metallic specimens processed via multiple manufacturing routes to assess impact of: ○ Metallurgical condition and defect formation ○ Manufacturing process variables ○ Surface condition ○ Heat treatment and thermal processing • Evaluation of impact of hydrogen on secondary hydrogen facing component materials (those that are not exposed to hydrogen under normal operating conditions but may be exposed to hydrogen under a loss of containment event), to understand impact of failure cases
Experimental testing	• Mapping of test capability • Industrial requirements capture for test parameter definition to define test matrix, to include temperature, pressure, hydrogen purity and phase, loading conditions, cooling rate, and time • Test parameter sensitivity analysis • Test standards gap analysis • Benchmarking of current test capability through round robin testing to evaluate repeatability and reproducibility • Study on the influence of manufacturing process on properties • Support supply of LH2 for testing • Sensor development for operation in extreme conditions • Validation of current sensor technology for operation in LH2 environment • Establishment of process for knowledge capture, data recording, and material test database • Development of long-term exposure testing capability • Two phase hydrogen flow meter development • Development of proxy fluid use cases • Development of tribology capability operating at 20 K

Challenge area	Proposed activity
Skills and knowledge sharing	• Sharing of good practice in the design of LH2 capable test capability • Creation of Community of Practice, to bring together experimental and simulation capability for knowledge sharing, workshops, and events, to include IAB and affiliates • Health and safety guidance documents to support cross learning and practical courses • Establishing an open access materials database, including fundamental properties, to support design and verification of modelling capability • Commissioning of PhDs and CDTs
Simulation capability	• Greater integration between simulation and experimental testing communities - development of framework to allow streamlined validation of simulation capability with experimental capability • Aerospace specific scenarios and operating condition definition • Evaluation of applicability of existing models to hydrogen environment and scenarios • Validation of current approaches against standardised test data • Development of multi-physics (including thermal, mechanical and chemical conditions) and multi-scale capability, bridging from nano- to meso- scale effects • Exploitation of experimental data and AI to support modelling capability development • Evaluation of requirements for certified simulation capability

Next Steps

This workshop has captured the current challenges related to fundamental materials behaviour for liquid hydrogen powered flight as viewed by the workshop attendees. Work will continue to map out the UK's capabilities in these areas and compare this to international capabilities. This work will identify gaps and opportunities for the UK, which, together with industry driven priorities, will identify where investment will give the maximum benefit to the UK. It is anticipated that this work will complete by April 2025, when a document laying out the recommended strategy for boosting UK capability in the field of liquid hydrogen fundamental and pre normative research.

To contribute to the UK mapping activity, please use the form in the following link: https://forms.office.com/e/HUf6cCSqb6

Appendix 1: Workshop Attendees

Organisation
Hydrogen Capability Network (HCN)
Hydrogen Innovation Initiative (HII)
HI-ACT
Airbus
Eaton
GKN Aerospace
Rolls-Royce
National Physical Laboratory (NPL)
UK-Aerospace Research Consortium (ARC)
University of Bath
University of Bristol
Cranfield University
University of Manchester
University of Nottingham
University of Sheffield
University of Strathclyde
Swansea University
Warwick University
National Composites Centre (NCC)
The Welding Institute (TWI)
UK Atomic Energy Association (UKAEA)
Henry Royce Institute