AEROSPACE TECHNOLOGY INSTITUTE

Hydrogen Capability Network

Cryogenic Hydrogen Health and Safety 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 requiring 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 cryogenic hydrogen health and safety challenges and potential solutions. The workshop was held on 16th April 2024, and it had 23 attendees from 18 organisations, including industry, research organisations, and academia.

The challenges were grouped into overarching themes coupled with associated sub-themes. Themes included: tools and infrastructure, standards, guidance and regulations, skills and competency, and developing the evidence base. A prioritisation exercise conducted at the workshop identified the following as sub-themes for development: modelling and validation, generation of good practice guides, test infrastructure, ignition and flammability mitigation, and low temperature hazards. A range of potential solutions/initiatives to tackle both the high priority and lower priority sub-themes were identified and are also detailed herein.

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.

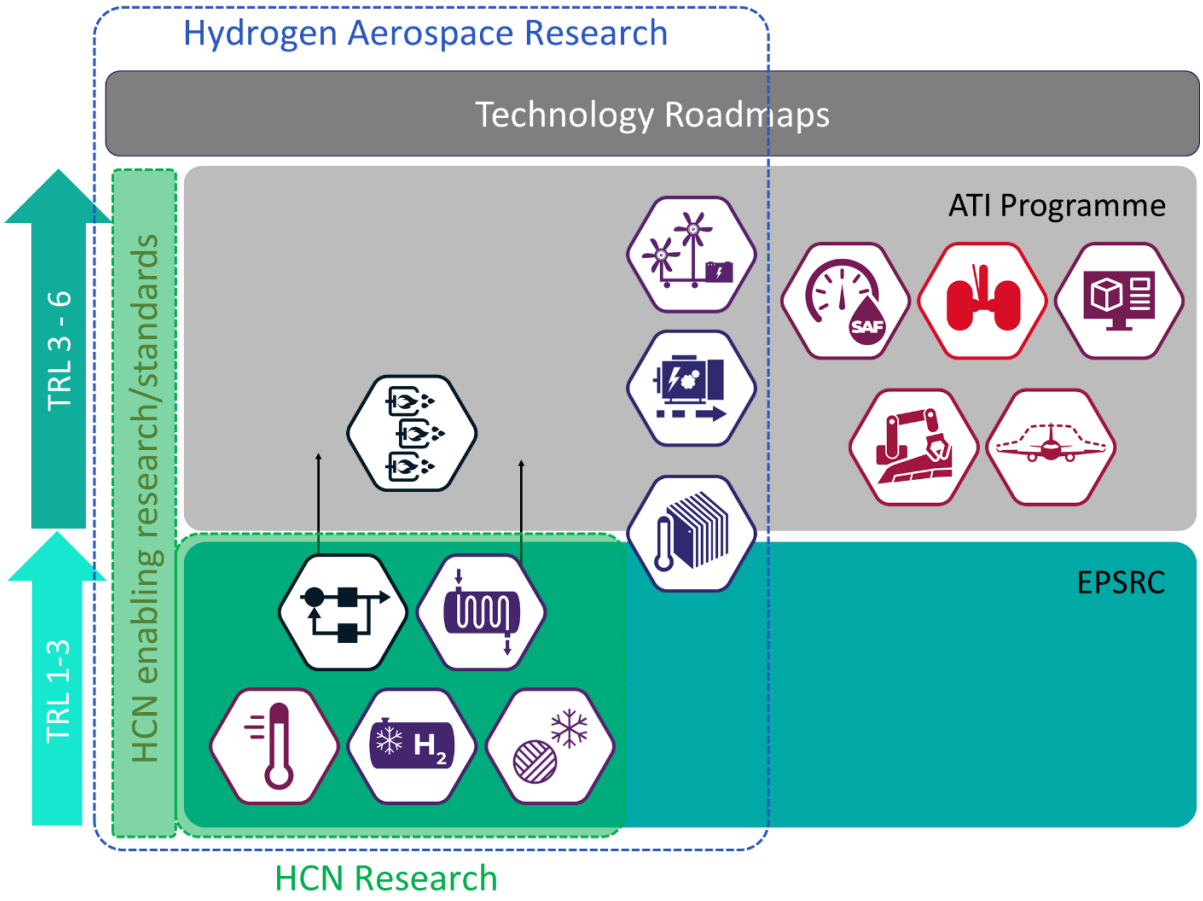

Figure 1 Technologies in which development is required to deliver LH2 powered flight

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

[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
- Fundamental material behaviour at cryogenic temperatures and hydrogen environments
- 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 feedback and outcomes from a workshop to capture the challenges and potential solutions for cryogenic hydrogen health and safety. The workshop was attended by 23 people from 18 organisations, including industry, research organisations, and universities, as listed in Appendix 1.

[2] Home - Hydrogen Innovation Initiative

Summary of challenges

Approach: the workshop participants were first placed in mixed academic and industrial breakout groups and asked to develop a list of the key challenges and issues in the field of cryogenic hydrogen health and safety that needed to be overcome to realise liquid hydrogen (LH2) flight. The discussions from all the breakout groups were then collated and grouped into a list of key topics that were then agreed amongst all participants.

The key topics that were identified, and the broader discussions that took place in the workshop under these topics, are summarised in the text below and the following sections:

- Tools and infrastructure
- Skills and competency
- Developing the evidence base
- Standards, guidance and regulations

Tools and infrastructure

There is a need for investment in test infrastructure that can conduct empirical work and experiments at various scales. Consideration should be given to both capability and capacity, and it should be taken in the context of existing facilities on a global basis. Initially, experimental work is likely to be predominantly pre-normative in nature by addressing key fundamentals, with learnings and proven protocols ultimately being embodied in normative standards. Specific challenges raised during the workshop included establishing the combined effects of loading and LH2 exposure, how LH2 behaves at altitude, sloshing, and the icing of components and structures. Security of supply of liquid hydrogen at the required quantities and quality is considered to be a key enabler and fundamental to achieving ambitions in this area.

The importance of sensor technologies and detection methodologies in general was highlighted, principally with respect to unintended hydrogen releases but also their broader potential in process control and quantifying losses along the value chain.

The complimentary nature of physical testing and simulation/modelling was noted, with data derived from experiments used to calibrate as well as validate models. As a concept this has broad applicability, but specific examples focussed on consequence modelling to understand further the ramifications of leaks in various scenarios, as well as sloshing and venting.

Lifetime prediction and the development of lifing tools were also considered to be important, and again these were likely to be informed by a combination of both physical testing coupled with simulation/ modelling.

It was acknowledged that there was a range of benefits that could be realised through the sharing of data, knowledge, and expertise. Specifically, a data-sharing framework was discussed along with the generation of generic open-source toolsets. While undoubtedly reservations or perceived blockers attributable to intellectual property rights would need to be addressed, the concept at least was deemed to have merit, particularly in the health and safety domain.

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

- Test infrastructure
- Sensor technology – capability and limitations
- Modelling and validation

- Knowledge/ data sharing
- Hydrogen – supply and condition
- Lifing tools

Skills and competency

Skills and competency development were seen as key enablers in the safe realisation of LH2 flight. A 'golden thread' relevant to the entire lifecycle and each part of the supply chain, it was felt that there was a pressing need to confirm learning needs and requirements that then could be addressed through the most appropriate means, including the provision of training material online and in-person. Specific reference was made to the development of competency in design, installation, and operations, particularly with respect to leakage scenarios and appropriate approaches to mitigation. Training and competency development with respect to DSEAR and ATEX were also highlighted.

It was recognised that a structured qualifications framework would likely be required for this with a view to demonstrating competency in relevant disciplines and at the level required. It was acknowledged that there would be a need to establish the applicability and reach of current aerospace know-how, derived over many years, and how relevant this would be for the safe realisation of LH2 flight. The workshop discussions also noted that there would be a need to break implicit assumptions and view hydrogen in the aviation context. Specific challenges were highlighted with respect to developing the necessary competencies to safely conduct testing at different scales.

Public perception of risk was raised, and challenges in other sectors highlighted to exemplify the importance of appropriate communications, education, and how these can influence social acceptance.

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

- Communication risk (link to social acceptance)
- Knowledge and skills base around existing regulations
- Hydrogen in aerospace context
- Competency around conducting tests
- Training across multiple levels

Developing the evidence base

At a fundamental level, there is a need to undertake a structured exercise to define the evidence base that is needed and required. It was noted that that there is an opportunity to learn from other sectors, but it will be important to validate the applicability of any findings in the aviation context.

The challenges identified covered a broad range of both preventative and mitigative controls. This is testament to the desire to control risks at source through consideration of a range of aspects such as design and material selection while also optimising the effectiveness of any mitigative approaches.

Specific challenges with respect to preventative controls include developing a comprehensive library of materials compatibility data to inform material selection in hydrogen environments and defining the performance criteria of control and monitoring systems. For the former, the library would be influenced by a range of factors including the material, the environment, and the applied loading. In the broader context of structural integrity, additional considerations include aspects such as component type (*e.g.* joints), geometry, and the metrics for determining ongoing integrity and by what means or methodology (*e.g.* capability of NDT).

Specific challenges with respect to mitigative controls relate to developing better understanding of low temperature hazards, such as condensation, liquefaction of air, phase change, hot or cold Boiling Liquid Expanding Vapour Explosion (BLEVE), leakage, and dispersion, alongside ignition and flammability considerations from hydrogen. Demonstrating the reliability and effectiveness of mitigative controls in the case of unintentional releases will be important, particularly in the context of preventing escalation.

The complete list of interest areas considered by the workshop is summarised as:

- Define evidence needed/required
- Low temperature hazards
- Ignition and flammability and mitigation methods
- Leakage
- Dispersion (inc. characteristics)
- Materials and structural integrity
- Aerospace specific requirements
- Control and monitoring systems

Standards, guidance and regulations

The development of a suite of good practice guides in key areas such as design and operations, purging, venting, and emergency procedures is an effective way of promulgating key learnings, promoting consistency, and acting as a complimentary resource to the development of normative standards.

There is a need to review existing aviation standards such as CS-25 and CS-E with a view to establishing the applicability of existing requirements, guidance, and acceptable means of compliance. Doing so will highlight notable exceptions and deviations as well as identifying knowledge gaps that need to be addressed by suitable means. It was suggested that updates/new standards would be required. Coupled with the above, it was suggested that there was a need to understand the applicability of regulations such as COMAH, DSEAR, ATEX, and Hazardous Substance Consent in the context of hydrogen aircraft/airport operations, along with a wide range of research and development settings such as universities, test houses, and experimental facilities.

The emerging regulatory landscape was discussed, including the respective roles of bodies such as the Civil Aviation Authority (CAA) and the Health and Safety Executive (HSE). Specific challenges related to both understanding the applicability of ground-based regulations to the aircraft setting and, in cases where they do not apply, any guiding principles that would be deemed to be good practice.

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

- Good practice guides – design and operation
- Applicability of standards and means of compliance
- Updated new standards
- Regulatory interfaces (HSE, CAA)

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 sum of these votes is provided in Figure 2, also indicating the different views or priorities of industry to research organisations.

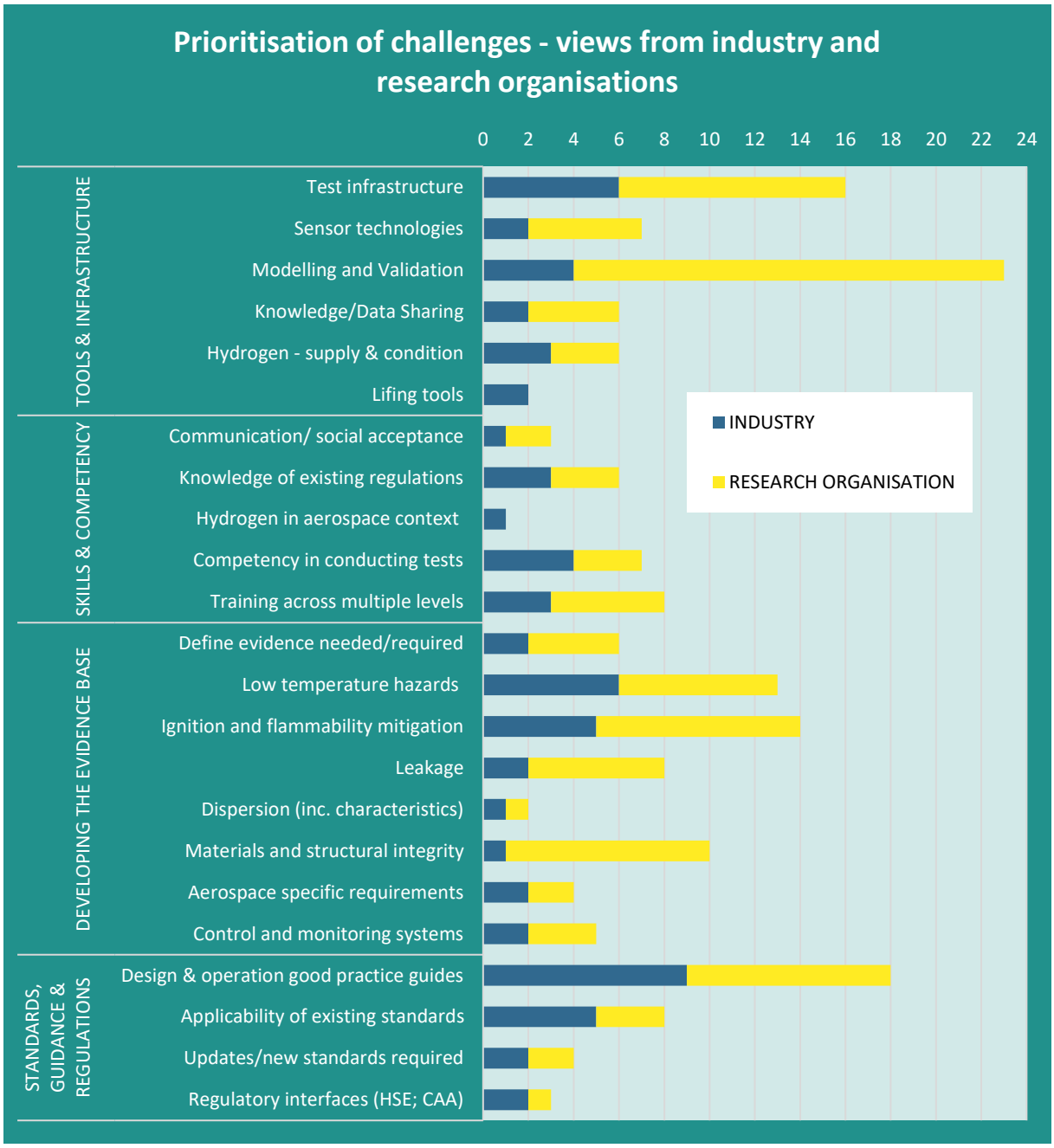

Figure 2: Technical priorities of challenges

Industry expressed most interest in the production of good practice guides, developing fundamental understanding of low temperature hazards, and the development of key test infrastructure to undertake physical testing. Research organisations expressed that priority should be given to the development of models and their validation, the development of key test infrastructure, and the generation of good practice guides.

Aggregating the votes from both industry and research organisations yields, in priority order:

1) Modelling and validation
2) Generation of good practice guides
3) Test infrastructure
4) Ignition and flammability and mitigation
5) Low temperature hazards.

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
Tools and infrastructure	• Creation of a centralised framework/platform for the sharing of data/ experience/knowledge in the LH2 domain • Research to establish the capability and limitations of sensor technologies and potential use cases, both in the RD&I landscape and in an operational context • Structured, systematic survey to establish UK LH2 test capability requirements • Landscaping review of existing LH2 test capability in the UK (and internationally), with a view to mapping existing capability against requirements • Explore the viability of a dedicated forum to be attended by both the modelling and physical/empirical testing communities, with a view to developing an integrated roadmap streamlining validation/calibration activities
Standards, guidance and regulations	• Gap analysis of existing standards such CS-25, CS-E, CS-APU, etc. • Cross-sectorial review to establish any regulatory insights, applicability, and overlap with other industries, particularly those that are highly regulated • Training offering aligned to regulations and standards • Read across from other hazardous cryogenic fluids such as LNG • Landscaping study to identify key international players and whether 'good practice' in other parts of the world could be adopted in the UK • Requirements and capability review of existing approaches to ensuring ongoing fitness for purpose – NDT, structural health monitoring, digital twins, etc. • Gap analysis with respect to emergency procedures and protocols including for firefighting, Jet A1 vs LH2, or an environment with both fuels in close proximity
Skills and competency	• Experiential learning initiative, to foster and develop practical skills with respect to the handling and use of LH2. There is an opportunity for this to be a complimentary initiative to test infrastructure development, facilitating skills and competency development alongside hardware development • Landscaping review to establish what initiatives are underway internationally, both with respect to aviation but also other sectors • Development of structured LH2 syllabus with complimentary qualifications framework • LH2 roadshow – practical demonstrations of technology

Challenge area	Proposed activity
Developing the evidence base	• Research into control and monitoring systems, requirements, and performance • State of the art evidence review and gap analysis, including work conducted in the UK by organisations such as DNV, HSE, NPL etc. • Research into unintended leaks, flammability, ignitibility, dispersion, ventilation, and model development • Practical, evidence-based information and guidance on handling cryogenic spills • Test programme to establish the compatibility of materials in LH2 environments, progressing to broader structural integrity considerations such as NDT etc.

Next Steps

This workshop has captured the current challenges related to health and safety for liquid hydrogen powered flight as viewed by the workshop attendees. Work will continue to map out the UK's capabilities in the areas highlighted and comparing them to international capabilities. These will identify gaps/ 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)
Advanced Manufacturing Research Centre (AMRC)
Zero Emissions Airports
Eaton
GKN Aerospace
Reaction Engines
Rolls-Royce
Unitrove
BOC
Civil Aviation Authority (CAA)
Cranfield University
Det Norske Veritas (DNV)
Health and Safety Executive (HSE)
University of Nottingham
University of Strathclyde
University of Warwick
Engineering and Physical Sciences Research Council (EPSRC)
University of Oxford