AEROSPACE TECHNOLOGY INSTITUTE

Hydrogen Capability Network

Cryogenic Hydrogen Fundamental Research Summary

FOR UK AEROSPACE

May 2025

About

This report was developed by the **Hydrogen Capability Network** (HCN) as a summary of the fundamental research for cryogenic hydrogen in aerospace and the gaps and opportunities for the UK. It is based on three external projects that analysed the global landscape for the critical research topics.

Disclaimer

The underlying data for the three detailed reports from which this summary is compiled is based on reviews of published information available before February 2025. Although every effort has been made to ensure it reflects a comprehensive review there will be research that was not available in the public domain, unable to be translated to English or not published due to commercial or security restrictions. The ATI does not accept liability for any errors, omissions or misleading statements and no warranty is given or responsibility accepted for any actions users may take based on the content of the report. The ATI reserves the right at any time to make changes to the material, or discontinue the report, without notice.

About the Aerospace Technology Institute

The **Aerospace Technology Institute** (ATI) is an independent organisation that works alongside government and industry to transform UK aerospace through technology and innovation. The ATI is funded equally by the **Department for Business and Trade** (DBT) and by industrial recipients of project grants who pay a small levy. ATI projects are chosen and overseen through close collaboration with Innovate UK and DBT.

As well as running this portfolio of R&T projects, the ATI conducts strategic research projects to help define and answer systemic questions of value to the UK aerospace sector. In 2022 the ATI published the findings of the **FlyZero** project, which concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft.

The ATI Programme has made several investments in liquid hydrogen technologies to support the next generation of zero-carbon aircraft. The Hydrogen Capability Network was launched in April 2023 with support from the Department for Business and Trade, to progress key recommendations from FlyZero which will enable the aerospace sector to deliver liquid hydrogen (LH_2) research & development (R&D).

Department for Business & Trade

Funded by the Department for Business and Trade.

Front cover image © ATI

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FlyZero's LH_2-powered, zero-carbon emission, midsize aircraft concept.

1. Executive Summary

The **Aerospace Technology Institute**'s (ATI) **FlyZero** project concluded that **liquid hydrogen** (LH_2) is the most viable zero-carbon emission fuel for decarbonising future commercial aircraft[2]. The technological change to a liquid hydrogen architecture is revolutionary with disruptive technology change needed to create a cryogenic hydrogen storage and fuel system.

There is limited global capability and a lack of validated data and understanding of the fundamental phenomena. Experts agree that to get to a certifiable, commercially viable system design, advancement is needed in the understanding of fundamental physics and chemistry. The **Hydrogen Capability Network** (HCN) identified three key areas that need to be supported, and this report summarises these detailed investigations of the global landscape for fundamental research into:

- **Material behaviour in cryogenic hydrogen environments**
- **Cryogenic hydrogen thermofluids behaviour**
- **Cryogenic hydrogen health and safety**

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The results show that this deficit in knowledge is global, with prior space industry-focused research not addressing aerospace needs. Activity has accelerated in recent years, and countries with an existing space industry have a competitive advantage, both in terms of a solid knowledge base from which to build and an established talent pool to develop the understanding. This increases the threat of industrial migration from the UK. Much of the current research focus, however, is modelling focused, validated with a sparse experimental database, much of which is over 50 years old.

A summary of the priorities is as follows:

For materials research

a key priority is developing increased confidence in and availability of materials test data. Testing standards were highlighted as critical to enable comparison of results and develop the confidence needed for aerospace certification.

For thermofluids research

a key priority is developing validated models for fluid systems. To do this, increased confidence in fundamental fluid properties is needed through more standardised testing, and more system level datasets developed to improve validation.

For health and safety research

a key priority is understanding the cycle of cause, development and consequence of liquid hydrogen system failures. Experimental data, improved models and good practice guides based on human factors are all needed.

A summary of the key findings for fundamental research in the UK:

- **Investment in fundamental research for cryogenic hydrogen is required to anchor industrial R&D in the UK and to fill the data gaps.**
- **To fill the data gaps experimental testing is required to generate datasets for model development, validation and certification. Testing must be standardised and repeatable.**
- **To undertake experimental testing, open access LH_2 test facilities are required, to reduce duplication, ensure LH_2 supply and maximise collaboration.**
- **All of this is required at pace and needs to be led by industrial requirements while allowing academic innovation, with data dissemination being critical to advancing development of capability in the sector.**

To deliver this, coordination is vital.

For the UK to maintain and build its global position in aerospace in the face of the disruption that LH_2 brings, an independent, industry-linked body is required to make strategic coordination decisions, convene research programmes and ensure rapid knowledge dissemination.

2. Introduction

The UK aerospace sector is a driver for growth, with a £30.5 billion turnover and over 104,000 skilled jobs[1]. Achieving aviation's commitment to Net Zero 2050 is a significant challenge requiring advancements in new fuels and aircraft technologies alongside out of sector measures. In 2021, the ATI FlyZero project identified LH_2 as the most viable zero-carbon emission fuel for future commercial aircraft. The project recognised novel hydrogen aircraft technologies would present risks and opportunities to the UK's existing strengths in wings, engines and fuel systems.

FlyZero identified which technologies are required to enable LH_2-powered aircraft and where gaps in this capability exist[2]. While the UK is strong in many of the relevant technology areas, the technological change to a liquid hydrogen architecture is revolutionary, with the cryogenic hydrogen storage and fuel system presenting a significant challenge. Designing a certifiable, commercially viable system requires a breadth of knowledge relating to cryogenic hydrogen that does not currently exist within the sector. Today, there is limited global capability and a lack of validated data and understanding of the fundamental phenomena. Accelerating fundamental research in this area will help the UK underpin the key areas of industrial strength to develop zero-carbon emission aircraft. The engineering capability and knowledge, for both fundamental research and industrial research, that is needed to develop cryogenic hydrogen storage and fuel systems and understand cryogenic cooling potential, will also support multiple other areas both within aviation and other sectors.

- **Material behaviour in cryogenic hydrogen environments**
- **Cryogenic hydrogen thermofluids behaviour**
- **Cryogenic hydrogen health and safety**

The HCN hosted workshops on these three topics to identify subtopics of particular interest to both industry and academia [3] [4] [5]. The HCN also commissioned a landscaping study to assess current global capabilities, determining current state-of-the-art, low Technology Readiness Level (TRL), fundamental research delivery timeframes, and identifying current or recently active non-commercial centres of capability. Historical seminal texts were also included to understand the state of global knowledge.

The outputs of these studies have produced the following HCN reports:

Cryogenic Hydrogen Materials
Global Research Landscape
led by the University of Sheffield with support from Oxford Research and Development Limited[6]

Cryogenic Hydrogen Thermofluids
Global Research Landscape
led by the University of Nottingham[7]

Cryogenic Hydrogen Health & Safety
Global Research Landscape
led by the University of Nottingham with support from the Health and Safety Executive (HSE)[8]

Each report highlights the global research status and gaps in which research and development is needed to enable the liquid hydrogen aircraft of the future, and this report summarises their findings.

An advisory board made up of major aerospace companies, the aerospace supply chain and start-up companies in aerospace and hydrogen established industry priorities. The advisory board membership is listed in *section 9*. This advisory board oversaw the landscaping activity to ensure its relevance to the sector stakeholders and generated a heatmap and priority list for each topic.

This report summarises the global research landscape in cryogenic hydrogen, identifying knowledge gaps and opportunities for the UK to lead in this field. The conclusions indicate gaps and opportunities for investment in research to secure UK market share in hydrogen-powered aircraft.

2.1 Methodology

The Hydrogen Capability Network ran an open tender for organisations to undertake a global landscaping exercise to understand the status of current global research in the three fundamental topics of priority to the sector. While all three projects looked at historical publications, available in the public domain, back to the 1950s and 1960s, the project was steered to focus the in-depth analysis of research output over the last decade. As such, prior to this the findings may not be as comprehensive.

The industry priorities were informed by workshops and through the advisory board. The heatmap and scoring rationale were generated by workshops with the advisory board. Members were asked to undertake a scoring exercise on priorities independently to avoid undue influence. However, members weren't forced to rank priorities only score based on their organisation's needs and their views of the sector. The reality was that this resulted in quite close scores with many topics being deemed an urgent priority (outputs needed within one to three years).

3. Context

3.1 Aerospace Requirements

Introducing liquid-hydrogen as an energy source for flight introduces new technological challenges. On conventional aircraft, kerosene remains in liquid state at near constant density throughout the journey from the tank to the point of use with only a small increase in temperature. In contrast, LH_2 will change from a liquid to a dense gas (supercritical fluid) and will undergo a temperature rise of around 300K between the tank and propulsion system, and hence the density of the fluid drops by an order of magnitude. This change in phase and density needs to be managed through a complex system of components, as illustrated in *Figure 1*, including pipes, connectors, valves, pumps and heat exchangers in addition to flow meters. Knowledge of the state and density of the fluid as it travels through this system is essential to ensure all components are sized to have the required flow capacity and that flow measurements and metering are accurate.

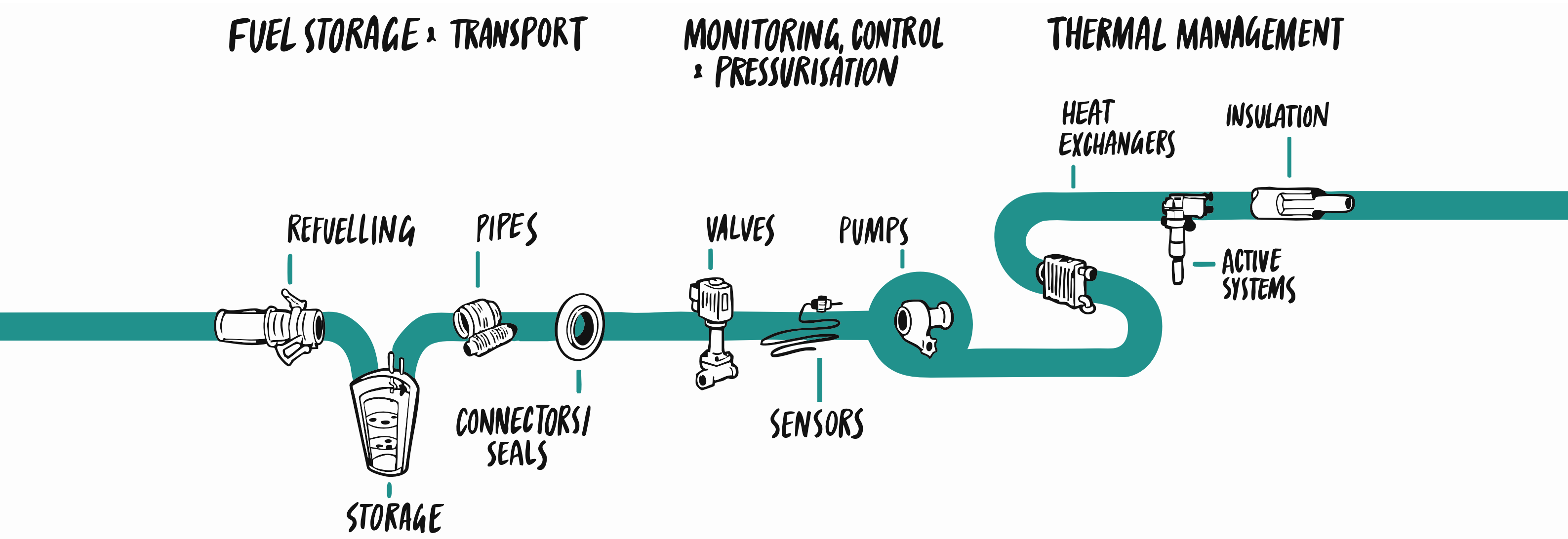


Figure 1 - Aircraft cryogenic hydrogen storage and fuel system schematic.

The cryogenic hydrogen storage and fuel system for aerospace must meet several requirements to achieve certification. The components and systems must have predictable lifespans of thousands of hours for reliable, safe operation and maintenance planning. The fuel system must be able to deliver turndown ratios, maximum flow/minimum flow, of 10:1 in a controlled, reliable manner within 10 seconds throughout the life of the components. Finally, the technology must be crashworthy, prevent human exposure to cryogenic temperatures and substances and manage hard to detect leaks.

Historically, LH_2 research focused on space industry needs, prioritising one-off performance over long-term hydrogen exposure and rapid fuel demand changes. Consequently, fundamental hydrogen thermofluids physics and chemistry remain underexplored for aerospace applications.

To develop and certify hydrogen-powered aircraft, materials must be selected and validated for the entire LH_2 fuel system, from storage tanks to heat exchangers. Components will operate at temperatures down to 20K (-253°C), with hydrogen exposure and varied temperature cycling. This creates challenges due to hydrogen embrittlement, internal stresses and significant property variations at near absolute zero temperatures.

As LH_2 moves from storage to use, it will transition from liquid to a dense gas (supercritical fluid) and understanding these states is crucial for safe and optimal LH_2 system design. Models combining these phenomena must be validated with robust materials data in representative conditions to simulate components and systems during the design process.

Health and safety for liquid hydrogen on aircraft, necessarily covers many scenarios and hazards including crashworthiness, health hazards to individuals when exposed to cryogenic temperatures and substances, catastrophic failures and barely detectable leaks which may develop into a hazardous situation.

3.2 Growth of Global Cryogenic Hydrogen Research

Globally, LH_2 technologies are focused on four main areas: space propulsion, maritime, heavy ground transport and civil aviation. Research dates to the early 1930s, with space propulsion being the first substantial application, scaling up during the 1960s space race. Recent developments in marine transportation, particularly by the Republic of Korea, Japan, and China, have become major areas of interest. R&D for marine and ground transport has led to significant publication and patent activity in Asia, ahead of civil aviation interest by at least five years.

Recent research for LH_2-fuelled civil aviation is mainly in Europe and the USA. *Figure 2* shows a significant increase in cryogenic hydrogen related research over the past five years, although it should be noted this study sought recent research to identify current global capabilities.

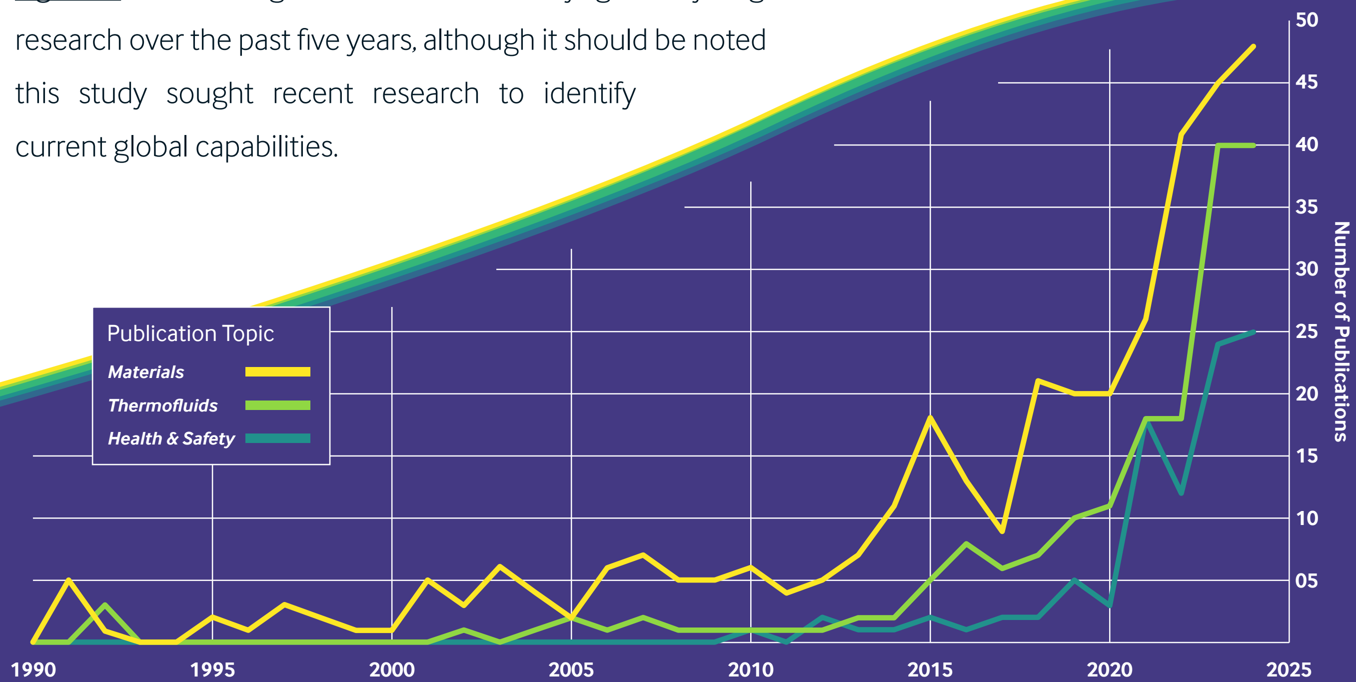


Figure 2 - Growth in publications in cryogenic hydrogen related research over time.

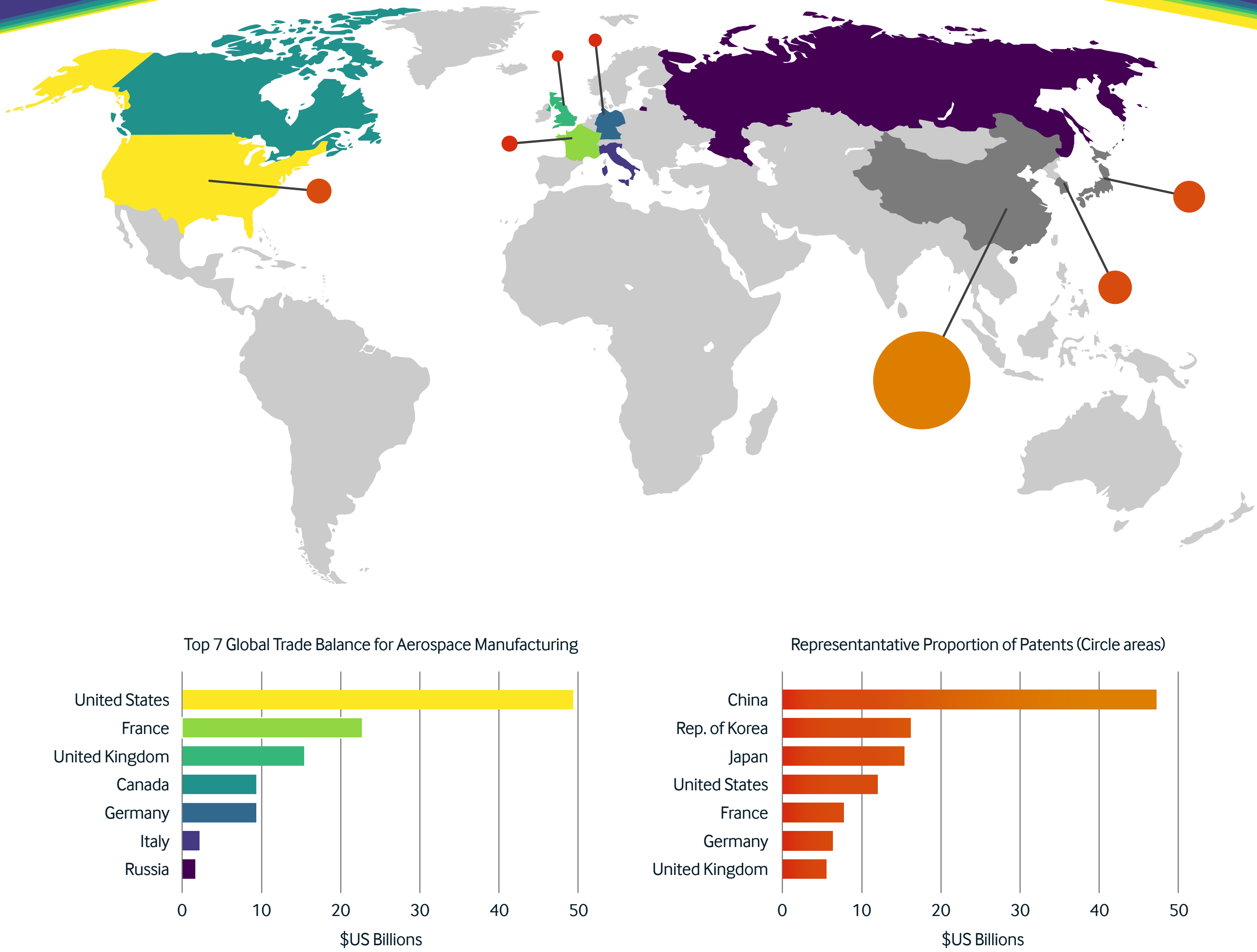


Figure 3 - Heatspots of top 7 countries with liquid hydrogen patent applications 2018-2024 (circle area indicates cumulative patent families) and aerospace manufacturing top 7 global ranking by trade balance $USBn, 2021 (shaded nations) [4].

LH_2-related patent applications shown in *Figure 3* indicate the conversion of fundamental research into pre-commercial R&D. Patent applications have increased fivefold since 2018, with China leading, followed by the Republic of Korea, Japan and the USA. Asia's patent activity ramp-up precedes that in the USA and Europe by at least five years, driven by interest in liquid hydrogen as an energy carrier and for road transport.

The UK ranks 7th in patent activity. Lower patent activity in the USA and UK compared to research paper publications suggests less commercial exploitation of fundamental research in these countries.

4. Materials

Understanding materials behaviour in cryogenic hydrogen environments is critical for the advancement of technology and product development for LH_2 aircraft. Data is required on the materials performance under different conditions in the cryogenic hydrogen environment. This will enable selection of materials which best offer lightweight, durable and safe solutions. Materials data and common test standards will be critical for aircraft certification.

4.1 Materials Research Summary

This study focused on measurements of physical properties, mechanical properties and hydrogen transport properties that lead to a fundamental understanding of material performance and the ability to model this[6]. Testing or modelling at the component or system level was not in scope. The topics analysed in this study were agreed by the advisory board through a workshop[4].

Figure 4 shows a ranking of the countries active in liquid hydrogen materials properties at cryogenic temperatures, coloured by the year in which the research was published, which demonstrates that activity is widespread. The highest levels of activity are in the USA and Asia, particularly China, the Republic of Korea and Japan, with a significant increase in publications over the last decade.

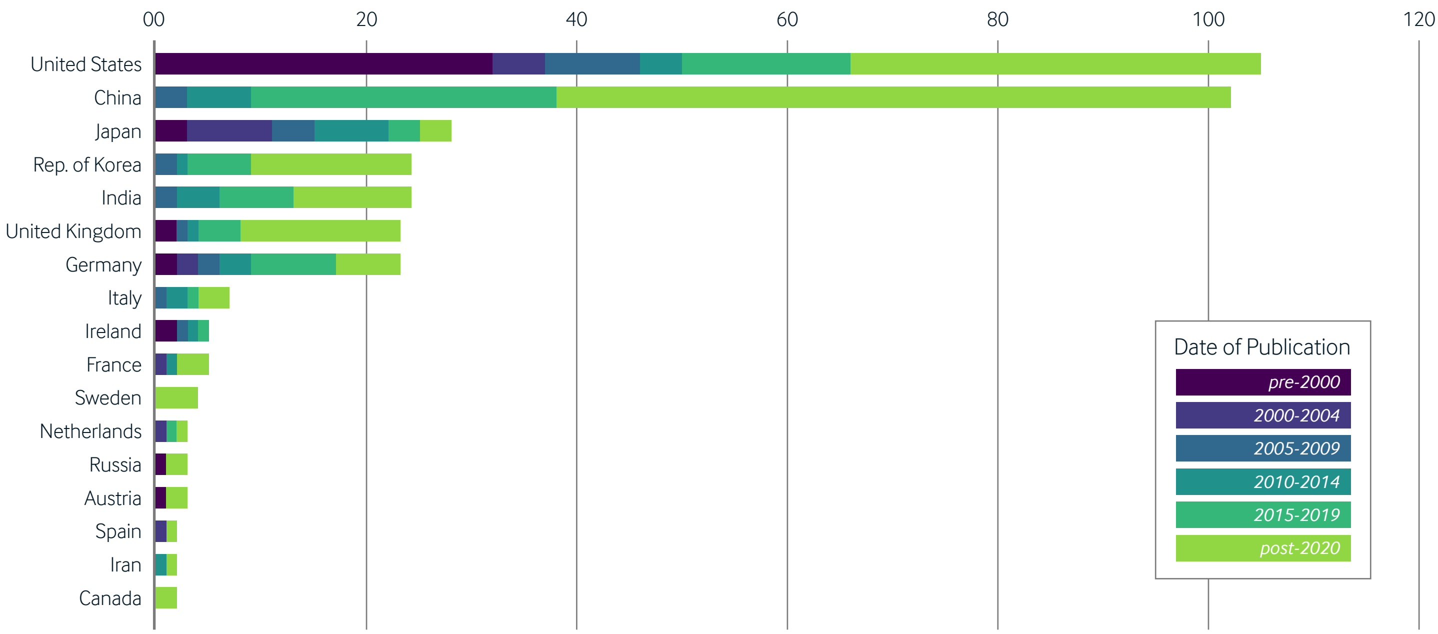


Figure 4 - Distribution of reviewed low TRL research publication counts in engineering LH_2 material properties by country and issue date.

Historically, the USA dominated the publications identified as relevant to liquid hydrogen materials properties. Since 2020, China dominates the publications space, with the USA falling to second place, followed by the Republic of Korea and the UK.

Of the available test data, large portions focus on short term hydrogen exposure primarily at liquid nitrogen temperatures of 77k or above. While some learnings from testing in these environments read across to our understanding of cryogenic materials behaviour, this learning is limited when considering the lifetime and breadth of operating conditions in a LH_2 aircraft fuel system.

This study found there is extremely limited facility capacity and standardisation globally to acquire data on mechanical properties at liquid hydrogen relevant temperatures, and even more limited capability to do this specifically in cryogenic hydrogen. Testing of mechanical properties at cryogenic temperatures is challenging. Even without the additional consideration of hydrogen, variables are more difficult to control, data is more difficult to acquire and sample access is challenging, with low test throughput. Data on thermo-mechanical fatigue of aerospace materials, particularly lightweight alloys, in the presence of cryogenic hydrogen is lacking.

For composites, comprehensive knowledge of the relationship between reinforcement structure, composition and macroscopic properties at cryogenic temperatures is deficient. This makes extrapolation to components more challenging due to the impact of three-dimensional form compared to two-dimensional test materials.

For all materials, there is a lack of capability across skills and infrastructure globally for long term or accelerated ageing studies for liquid hydrogen compatible materials. Thermal cycling history is important to consider, as cryogenic temperature exposure permanently alters the structure of a wide range of materials including composites and metals, introducing new hydrogen trapping centres in some metals.

Equipment and methods are not standardised at most levels which can significantly impact results. In particular, there is a low level of standardisation of test methods for measurement of mechanical properties at cryogenic temperatures between laboratories. Equipment is custom designed with a wide range of cooling, charging, test frame integration and measurement methods. This limits understanding of the impact of these methods and the sensitivities of results. The impact of manufacturing methods is partially understood for cryogenic conditions but extremely limited for their influence in liquid hydrogen environments.

Compared with mechanical property testing, physical property testing of materials at cryogenic temperatures is more consistent between laboratories, due to the wide adoption of Quantum Design Physical Properties Measurement Systems (QD PPMS). Modelling to link materials test data to component performance and service life at cryogenic temperatures is immature. Fundamental to this is the lack of standardised experimental data to validate models. Multi-physics modelling capability linking physical and mechanical property test results to material micro and meso scale structure at cryogenic temperatures is relatively immature.

A complementary study[9] by the HCN collated cryogenic and hydrogen materials test capability to understand the UK's ability to conduct fundamental materials research. Similar to global capabilities, there is extremely limited capacity for mechanical testing of materials in cryogenic hydrogen test environments. Cryogenic mechanical behaviour of materials below 77K may be evaluated at only few sites of limited capacity. Inert-atmosphere, cryogenic thermophysical property testing is available at multiple sites, however there is no capability to conduct testing in a hydrogen environment. Hydrogen transport within materials is, however, evaluated at multiple locations and there has been work to benchmark these, including under liquid hydrogen conditions. Broader capability for micro/nano-scale testing in cryogenic or hydrogen environments is limited, along with specialised testing for the evaluation of tribology or other phenomena related effects.

4.2 Materials Industry Priorities

Materials research sub-topics evaluated in this study were selected through a workshop[4]. Scoring was provided by the advisory board members to indicate priority for their organisation, with the materials results given in *Figure 5* below.

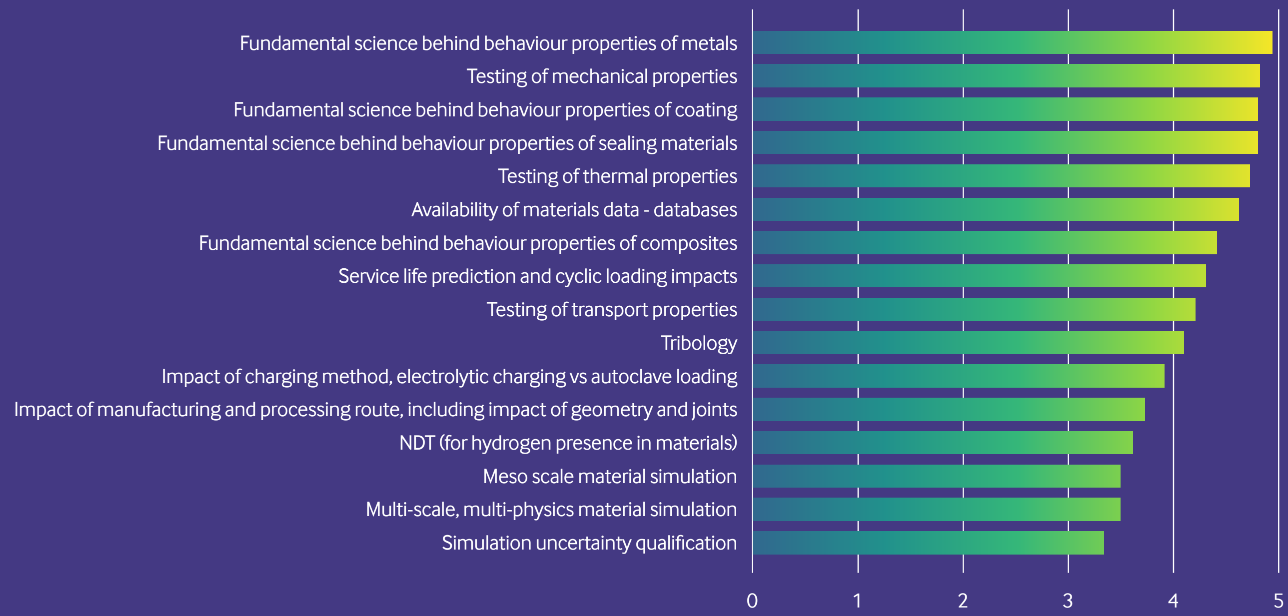


Figure 5 - Industry priorities for liquid hydrogen material research.

This graph highlights that the understanding of this wide spectrum of fundamental materials behaviour is urgently required with all topics being assessed to be required within three years. It was also clear that all topics were required for product design and certification in the UK and may provide knowledge applicable within other sectors, indicating that the lack of knowledge in these topics is hindering product development.

Further examining the responses, the research topics may be split into three levels of priority. Top priorities described as being required within a year include understanding behaviour of metallic materials, sealings and coatings and access to experimental data with mechanical and thermal properties required urgently. Secondary priorities required within one to two years include the understanding of composites behaviour, transport and tribology properties and the ability to perform service life predictions. Topics of lower priority, required to be addressed within the next three years, include the understanding of the impact of manufacturing and processing route on material behaviour, non-destructive testing to evaluate hydrogen presence in materials, and simulation capability, reflecting the dependency of modelling on the establishment of experimental test data required for validation.

4.3 Materials Conclusions and Recommendations

Reviewing global fundamental materials research in cryogenic hydrogen environments, industrial priorities, and UK capabilities, the following recommendations are made:

- **There is a need to standardise equipment and methods in order to allow the cross-comparison of experimental work and contribute to an expansion of global capacity effectively. New capability will soon be online to perform required testing in the UK, so focused activity on standardisation would be globally impactful.**
- **First actions post-standardisation should prioritise the development of experimental data to support modelling capability. In particular, there is both a high need for and extremely limited capability globally, to acquire data on mechanical properties at liquid hydrogen relevant temperatures and in cryogenic hydrogen.**
- **More experimental capability should be developed to understand behaviour of sealant and coating materials, in relation to physical, transport and mechanical properties, followed by test campaigns to evaluate material performance.**
- **For metals where data on the combined impacts of fatigue cycles and thermal cycles in cryogenic hydrogen is lacking, and there is a global lack of capability for long term or accelerated ageing studies for liquid hydrogen compatible materials, efforts should be made to develop methods for accelerated testing.**
- **For composites, comprehensive knowledge of the relationship between reinforcement structure, composition and macroscopic properties at cryogenic temperatures is needed, to make extrapolation to three-dimensional components possible.**
- **Collaboration to allow data sharing of standardised material datasets and improvements to modelling performance and service life would enable the development of liquid hydrogen technologies for aerospace at pace.**

5. Thermofluids

Low-TRL research into the thermofluid behaviour of cryogenic hydrogen, including liquid, supercritical, and multiphase states, is necessary to enable the use of LH_2 in aircraft. As with the materials and health and safety topics, fundamental thermofluid behaviour research is applicable to multiple sectors including energy, transport, defence and others.

5.1 Thermofluids Research Summary

The interest in LH_2 and its thermofluidic behaviour is increasing, as can be seen by *Figure 6* [7] showing a rapid increase in journal publications since 2000 across a wide range of TRLs, it also ranks the countries most active in LH_2 thermofluid behaviour research over time. Most publications are modelling investigations primarily using data from the mid-twentieth century, while only a small percentage of the publications focus on experimental work.

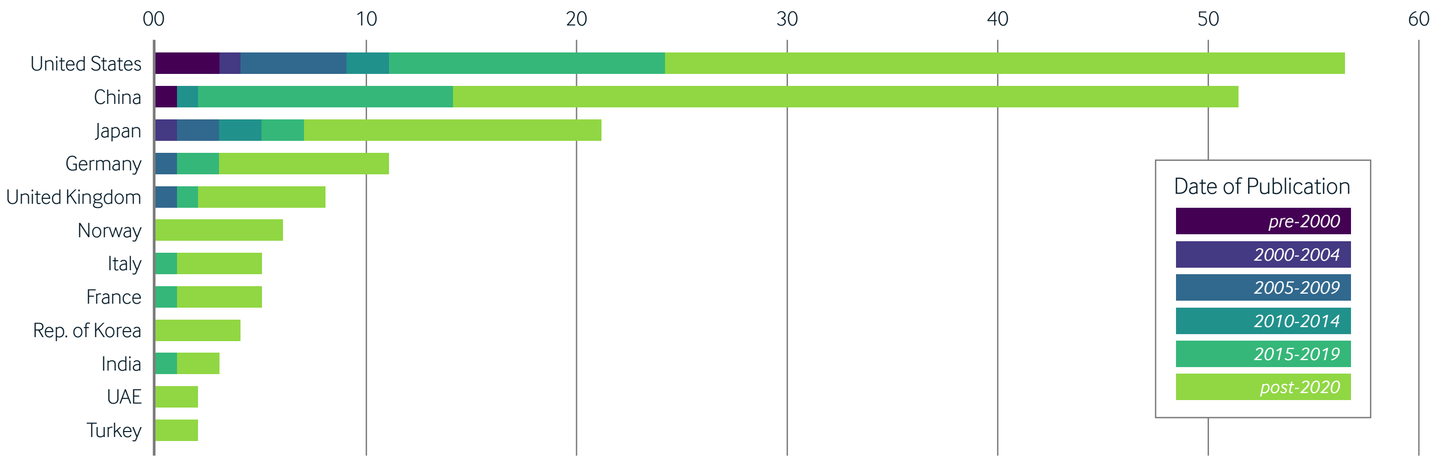


Figure 6 - Distribution of reviewed low TRL research publication counts in engineering LH_2 fluid properties by country and issue date.

Stemming from a workshop that identified topics requiring further investigation[5], research investigated related publications in detail and identified gaps where further work is needed[5]. These same topics were considered by the advisory board, who ranked their key topics required for further consideration, as can be seen in *Figure 7*.

One important area identified with a need for further research was the fundamental fluid properties of cryogenic hydrogen both as a liquid and supercritical fluid, particularly around phase boundaries and the critical point. This data is required as input into models to be able to develop accurate predictions of liquid hydrogen system behaviour.

The review found that most experimental data being used was gathered in the mid-twentieth century. This experimental data gives a good basis but there are gaps and variations between the experiments leading to measurements at phase boundaries and at the critical point having high levels of uncertainty. These datasets are used in the NIST database[10] and associated REFPROP[11] software, which are the standard reference sources for LH_2 properties and equations of state.

Ortho-hydrogen

Both hydrogen atoms spin in the same direction

Para-hydrogen

The two hydrogen atoms spin in opposite directions

Normal hydrogen is made up of 25% para-hydrogen and 75% ortho-hydrogen. When cooling hydrogen gas from room temperature to normal boiling point, ortho-hydrogen converts to para-hydrogen spontaneously in a process known as an exothermic reaction. At cryogenic temperatures, hydrogen is almost entirely para-hydrogen.

Molecular hydrogen (H_2) has two different spin states, ortho- and para-hydrogen, and the spontaneous conversion between the two can release heat. One of the more active areas of fundamental LH_2 research is around ortho-para hydrogen conversion and associated understanding through both experiments and modelling. However, understanding of the impact of different ratios of ortho and para-hydrogen on fundamental fluid properties is limited, with data usually only covering normal hydrogen (25% para-hydrogen) or 100% para-hydrogen.

Across all thermofluids topics the USA and Japan have the most publications focused on experimental research. In both instances, many of these facilities link with national space organisations. There are also research groups at universities who focus on LH_2 research, notably the HYPER lab at Washington State University in the USA. Development of LH_2-suitable laboratories can be expensive and requires specialist knowledge, although the body of data would benefit from having more LH_2 experimental facilities to address critical gaps, and validate existing datasets. Within the UK there are currently no universities or research institutions with existing LH_2 test facilities to investigate LH_2 thermofluids understanding.

Globally, publications on modelling research are significantly more numerous and widespread than those focusing on experiments. Most modelling journal papers are from China, although there are also large numbers from Europe, Australia, Japan, and the USA. Some of this work is published incrementally through multiple papers, and most of it relies on the historical fundamental data, such as that in REFPROP with limited additional validation.

Experimental data and fundamental modelling in transient and multiphase systems was identified as an important gap. One example is the need for more experimental data in boiling and phase change regimes, such as heat transfer coefficients and information on thermal expansion. On experimental sensors, there are suitable existing sensing techniques for basic experiments, and modern methods such as neutron imaging and optical techniques can help gather this information.

The industrial advisory board identified heat transfer and pressure work as needed imminently for product development. The literature review found that while there is ongoing experimental and modelling research in heat transfer and bubble formation, there are gaps in information and few experimental facilities in which experiments can occur. Numerical models of systems are being developed, but these frequently rely on historical data from NASA or validation from other cryogenic fluids, such as liquid nitrogen. Less ongoing research was found in relation to work and cavitation in LH_2 systems, although modelling relating to scenario development in which these phenomena are critical (such as pumping) was found to be active.

Little research has been found in regard to LH_2 in magnetic or electric fields. There has been some work on the use of LH_2 as coolants for superconductors in large magnetic fields but this does not focus on the properties or behaviour of the LH_2 beyond its cooling effect. Additionally, the impact of magnetic or electrical fields can link with ortho-para hydrogen conversion. Although the direct need for experimental and modelling work in these areas is not as clear as that for other areas (such as fundamental fluid properties or heat transfer), this gap may be relevant for future technologies. However, it is not a gap requiring extra immediate research.

The literature review of modelling techniques highlighted the same uncertainties around the underlying data. Many complex modelling techniques such as computational fluid dynamics (CFD) including direct numerical simulations (DNSs) have tuneable parameters which must be set by the modeller. These parameters can have a significant influence on the outcome of the simulation. Simulations and modelling are a key part of aerospace development and certification, and whole system modelling, when supported by experimental data, will allow LH_2 system design and development to be accelerated. Therefore, the experience and knowledge of the modeller using these techniques can impact the result while more reliable data may make these modelling techniques more mature and robust.

The thermofluids report also identifies some interdisciplinary gaps which link with the health and safety and materials research. These include:

- **The interactions of LH_2 and surfaces. Surface interactions link closely with phenomena such as heat transfer, boiling, and flow regimes, and this work links closely with tribology.**
- **Work and cavitation, which links closely with materials as well as multiphase flow and boiling. Damages to surfaces by cavitation can have knock-on effects on material properties.**
- **Flow and dispersion of hydrogen, particularly in relation to the health and safety consequences of unwanted LH_2 releases.**

5.2 Thermofluids Industry Priorities

A list of topics was put to the industrial advisory board for ranking with *Figure 7* showing the averaged outcomes. A score of '3' in indicates that industry feels development is needed within approximately the next three years. All topics score '3' or higher, indicating that the advisory board felt all topics are required for product development. This point highlights that the lack of fundamental thermofluid data on LH_2 is hindering product development at this stage.

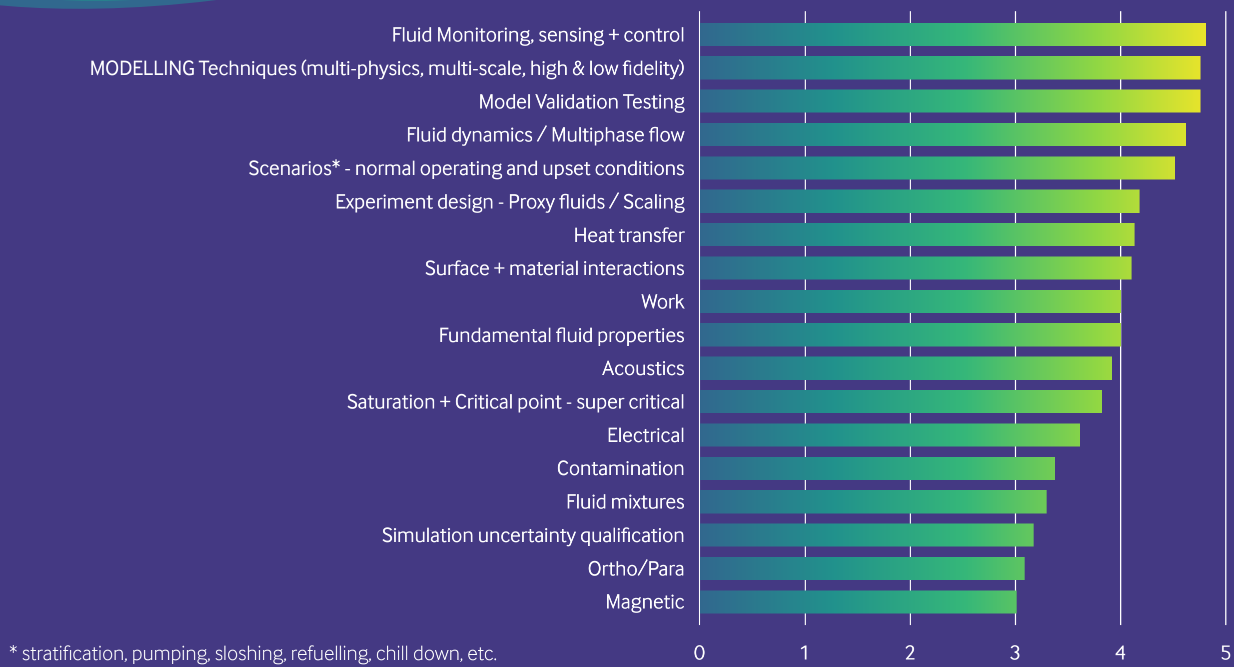


Figure 7 - Industry priorities for liquid hydrogen thermofluids research.

The advisory board was asked to estimate the timeframes needed for the development of these key topics, with the most urgent occurring within one year and the least urgent not needed within five years. The overall results show that activity in all topics is viewed as being required within a three-year time frame.

One area the advisory board highlighted as critical (i.e. within one year) was the need for fluid monitoring, sensing, and control. However, the low-TRL research report noted that there are existing techniques for LH_2 fluid sensing. Further investigation has shown that there is a difference in definition between the low-TRL research and the requirements highlighted by the advisory board. The former focused on what is needed to identify basic fluid phenomena in a controlled laboratory environment. The latter considered sensors needed on-aircraft, such as those needed to measure flow through the fuelling system or level within a LH_2 storage tank mid-air. This dichotomy highlights that sensors which are suitable in a laboratory environment do not necessarily cover higher TRL requirements which are needed to enable technology development. A separate report on mid-TRL sensing technology for LH_2 aircraft conditions has been developed[12].

Other areas in which the advisory board highlighted that data was needed in the next one to three years were modelling techniques and validation, scenario analysis, heat transfer, acoustics, surface interactions, and electrical fields interactions.

5.3 Thermofluids Conclusions & Recommendations

The main gaps and recommendations from the summary report[7] as well as the advisory board can be summarised as follows:

- **Experimental data on fundamental fluid properties is needed as much of the currently used data is from the mid-twentieth century and has some scatter and uncertainty, particularly around phase boundaries and the critical point.**
  - **Standardisation of data will allow independent experiments to be compared to each other.**
  - **Experimental data on transients, data around phase change boundaries and the critical point, and heat transfer were identified as key gaps which needed to be addressed.**
  - **These fundamental fluid properties form the inputs on which models rely and improving the accuracy of the properties will improve the outputs of the models.**
- **More experiments and modelling are needed on heat transfer and work, specifically on bubbling and cavitation. Both phenomena link with fundamental materials properties. Furthermore, pumping was identified as a key scenario for investigation; these phenomena link closely with this scenario.**
- **Improved datasets for validation will enable model and modelling techniques to be developed increasing their accuracy and accessibility reducing the need for knowledgeable and skilled modellers to understand the limitations of the software which is in part due to uncertainties around the underlying thermofluidic data.**

6. Health and Safety

Health and safety (H&S) when applied to such a broad application as use of liquid hydrogen on aircraft, necessarily covers many scenarios and hazards all of which must be thoroughly considered and addressed. This includes crashworthiness, health hazards to individuals when exposed to cryogenic temperatures and substances, catastrophic failures and barely detectable leaks which may develop into a hazardous situation. However, any hazardous situation will originate from a failure of some sort, whether mechanical, human, a loss of containment or control etc. creating a potential safety risk, the consequences of which may create the H&S hazard.

To have a strong grasp of the health and safety risks associated with the use of liquid hydrogen, three stages need to be equally addressed, namely originating failure modes, development of a hazardous situation, and consequences. Some of the originating failures due to material or fluid behaviour are discussed in *Sections 4 and 5*. The remaining causes and subsequent development into a hazard are considered in this Section. The specific challenge with liquid hydrogen is that its behaviour is still not thoroughly understood and hence all three of these stages can potentially be very different to current experience and understanding making mitigation and prevention strategies difficult to define. Therefore, in order to have confidence in creating liquid hydrogen fuelled aircraft, a significant body of knowledge is required from fundamental material and fluid behaviour through to large scale dispersion and ignition phenomena.

6.1 Health and Safety Research Summary

The interest in LH_2 and its thermofluidic behaviour is increasing, as can be seen by *Figure 6* [7] showing a rapid increase in journal publications since 2000 across a wide range of TRLs, it also ranks the countries most active in LH_2 thermofluid behaviour research over time. Most publications are modelling investigations primarily using data from the mid-twentieth century, while only a small percentage of the publications focus on experimental work.

Figure 8 shows a ranking of the countries active in liquid hydrogen engineering safety, coloured by the year in which the research was published, indicating a steady increase in research outputs since 2000, with numbers doubling each decade. HySafe Network of Excellence for the European Commission became the fully independent International Association for Hydrogen Safety (IA HySafe) which catalysed and coordinated activity investigating the safety of hydrogen as an alternative energy source across the TRL spectrum.

The review found the cross-over between the materials, thermofluids and health and safety fields is clear from publications, and evidences the need for cross-disciplinary teams to ensure robust research.

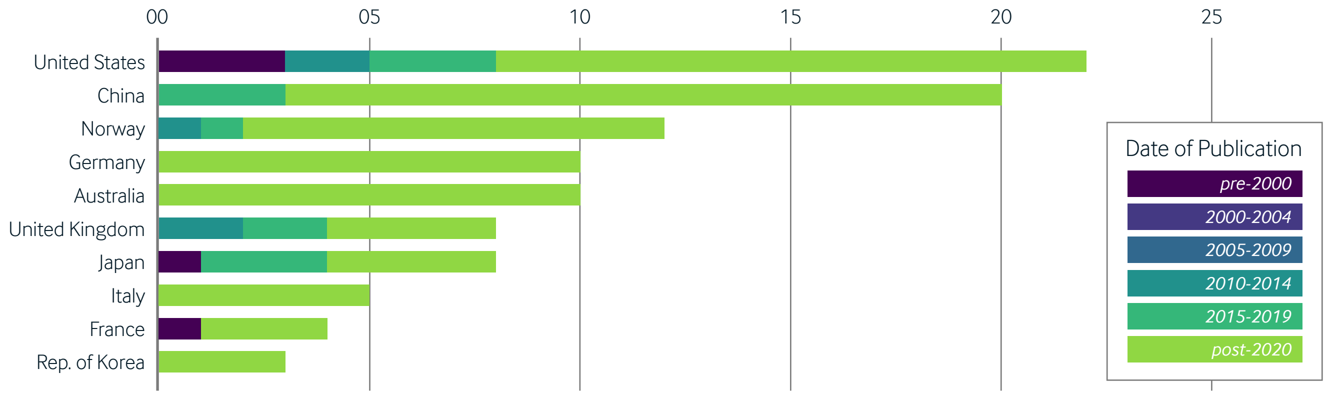


Figure 8 - Distribution of reviewed low TRL research publication counts in engineering LH_2 safety by country and issue date.

A number of countries were found to have liquid hydrogen capability, but often focused on space applications, with only four having capability specifically looking at safety relating to liquid hydrogen as a fuel. The UK is one of those countries with two sites, HSE and DNV, providing world-leading capability, with the other countries being the USA, Japan and the Republic of Korea.

While the outcomes of leakage have been defined there is a lack of data, and often differing outcomes, recorded in the literature. For instance, a jet of liquid hydrogen does not always lead to a fireball, nor does a liquid hydrogen pool always exhibit the same behaviour. Liquid hydrogen release can result in a two-phase jet dispersion leading to liquid hydrogen pools, subsequent vaporisation and formation of potentially dense hydrogen gas clouds. The impact of the liquid hydrogen release on the surrounding temperature can also result in the formation of solid or liquid nitrogen and oxygen. Where gaseous hydrogen leaks do not ignite, they still pose an H&S risk as a possible asphyxiation risk where leaks are contained within a volume rather than dispersing.

Experimental liquid hydrogen dispersion data has been generated since the 1950s. However, there are significant gaps in understanding the multiphase behaviour of liquid hydrogen from the leak point through to the far field dispersion. Six experimental facilities have been active in this area, again with two of those being in the UK. It was noted that tank pressure, temperature and flow rate were controlled as part of the testing protocol and that environmental conditions have a significant impact on the outcomes.

Experimental ignition data, linked to safety, is limited and requires standardisation. The presence of catalytic materials, impurities, dust and humidity as well as differences in environmental and experimental conditions lead to apparently contradictory results. This however is a key area where existing UK facilities, and research strength, could be harnessed to provide data and standardisation principles.

There are limited publications of experimental work characterising the behaviour of liquid hydrogen leakage from cracks, orifices or component architecture which is necessary to formulate accurate source term data for modelling studies. Experimental data relating to fragmentation and the size and duration of liquid hydrogen fireballs and heat radiation from them is also lacking. There is also a need to compare the consequences of boiling liquid expanding vapour events (BLEVEs) with other conventional fuels to ensure that health & safety codes and regulations, are fit for purpose.

Though many modelling publications mention liquid hydrogen leakage studies, they are often more focussed on the dispersion and formation of hydrogen clouds than the analysis at the leak point and associated near field. Modelling of liquid hydrogen safety is dominated by China with many publications being incremental and generally reliant on experimental validation from other countries. Across all papers, there is agreement that the key model leakage parameters are leakage pressure, leakage rate, direction, wind speed, wind direction, spill rate and spill duration. Predictions provide evaporation rates, flammable volume of the hydrogen cloud, and where a full dispersion model is linked to a leakage model, the maximum downwind distance/height.

Four computational fluid dynamics (CFD) tools have been identified that provide bespoke simulations for hydrogen release and dispersion. These are FLACS, Boilfast, ADREA-HF, SINDA FLUINT (Thermal Desktop). In addition, commercial CFD codes such as Ansys Fluent and Siemens Star-CCM+ have been utilised for modelling release and dispersion. The level of validation of these tools is not clear given the restricted experimental data sets. HyRAM+, a software toolkit, is openly available and can be used to assess the safety in the use, delivery and storage infrastructure of liquid hydrogen and other alternative fuels.

Human factors in the context of this work refers to human behaviour either as a root cause of a hazard (i.e. 'human error' leading to a safety risk) or human behaviour when faced with a hazard. Human behaviour is especially relevant when that hazard is from an unfamiliar substance which may be behaving in an unfamiliar way such as would be the case with a liquid hydrogen leak or spill. In the latter case low TRL research would seek to understand instinctive responses to liquid hydrogen hazards and whether those responses would potentially make the situation better or worse. Such research would result in guidance, procedures and training to ensure as far as possible that human behaviour and actions do not lead to safety risks but result in appropriate actions should a hazard occur. No publicly available publications were found during this work on the human factors element of liquid hydrogen safety, indicating a lack of research across low to high TRL. This is a key strength in the UK that could be leveraged at relatively low cost by translating research from existing expertise in the transport sector.

6.2 Health and Safety Industry Priorities

The advisory board prioritised which topics are required for low TRL research from an industry perspective in order to achieve liquid hydrogen powered flight, shown in *Figure 9*. It should be noted that the members of the advisory board were predominantly engineers and technical experts, which may have biased the results towards those subjects rather than the human factors and low temperature hazards topics. Subsequent discussion acknowledged the importance of those areas in a safety context.

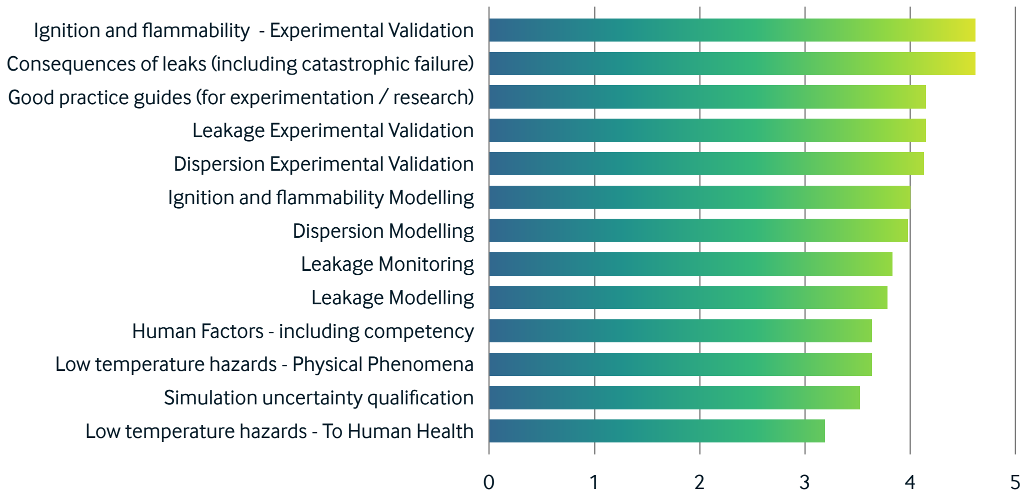


Figure 9 - Industry priorities for liquid hydrogen health and safety research.

The greatest identified need, and hence highest and most urgent priority, was for experimental data at all scales, from initial failure conditions to the development of a hazard (leak/near-field phenomena) through to far-field, long term dispersion, all with associated ignition behaviour. There was little differentiation between the priorities across these scales indicating that all were needed to the same extent.

Modelling work across the same range of scales would be the next priority, presumably because the experimental data is a pre-requisite for accurate modelling, the real-world data providing input conditions and verification information.

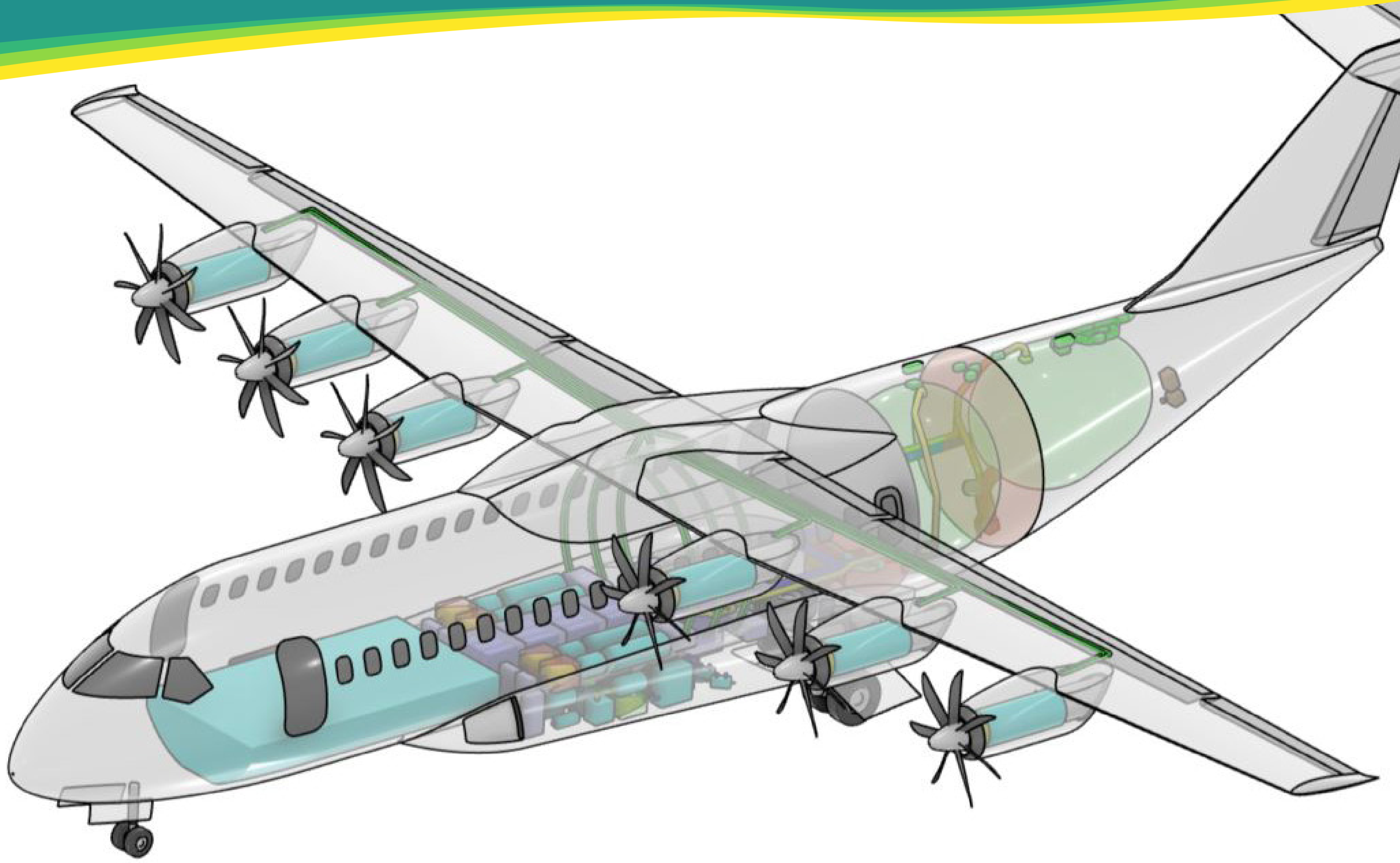
An additional high priority was for good practice guides for experimentation and research with liquid hydrogen, although it could be argued that this is higher TRL and would naturally follow on from increased experimental work.

The application for this research was also assessed, with design and certification needs being immediate with manufacturing requirements less so.

6.3 Health and Safety Conclusions & Recommendations

The main research gaps and recommendations for research investment based on this work are summarised below:

- **Experimental data of hazards involving liquid hydrogen is very scarce, and yet essential in order to create and verify computer models, and to generate information for design and certification. This should therefore be the highest priority for low TRL research. The UK has a level of expertise for both liquid hydrogen leakage and dispersion at HSE Buxton, while DNV Spadeadam provides large scale release facilities. This area is therefore one in which the UK can remain world-leading.**
- **Experimental ignition data, linked to safety, is limited and requires standardisation. This is a key area where existing UK facilities, and research strength, could be harnessed to provide data and standardisation principles.**
- **There are no publicly available publications on the human factors element of liquid hydrogen safety, indicating a lack of research across low to high TRL. The UK has key strengths that should be leveraged at relatively low cost to translate research from existing expertise in the transport sector.**



Cryogenic hydrogen storage and fuel system within FlyZero's LH_2-powered, zero-carbon emission, regional aircraft concept.

7. Summary & Conclusions

7.1 Key Findings from Global Landscaping Research

In all topics publications on cryogenic hydrogen have grown exponentially over the last 10 years,

with most recent focus on cryogenic hydrogen as an energy vector. The USA is leading in the number of publications, due to having the longest history of research in this area borne out of its space industry. Over the last decade China has rapidly increased research and patent applications, often incremental and modelling based, which put it well ahead of other nations. Monitoring of China's progress is essential to see if it gains a competitive edge, as it did in the battery industry. Japan and the Republic of Korea are also active, focusing on marine applications. The UK has two of six experimental facilities active in investigating safety aspects associated with LH_2 as a fuel, but these must be fully exploited and research output increased. This is especially important as countries with facilities with large volume LH_2 supply could easily pivot into this area as shown in the joint NPL & HCN report on the international test infrastructure[13].

A lack of experimental data is likely to impact the usefulness of historic and recent research.

A significant contribution to the more widespread activity across thermofluids and health and safety has focused on modelling, relying on sparse data often from the 1960s space industry. The usefulness of existing data, including materials data, is limited by the lack of standardised test procedures, making comparisons difficult. Additionally, data generated for the space industry does not meet many aerospace needs, such as the impact of long-term hydrogen exposure on materials, system design for a wide range of fuel flow rates, and widespread training for safe hydrogen handling and use. Addressing this data deficit is crucial to develop the reliable tools needed for technology advancement.

Research gaps that need to be addressed:

Materials

Significant gaps to be addressed include the understanding of multiple materials properties under cyclic mechanical and thermal loading, for metallic and composite materials, so to understand lifespan under cryogenic hydrogen exposure and increase options for lightweight storage solutions. More research is needed on how manufacturing and joining techniques affect material properties and system endurance to develop reliable system lifing assessments.

Thermofluids

Understanding the impact of pressure rise and heat transfer across the fuel demand cycle is vital, as both affect where hydrogen changes phase, especially for safe fuel system response during transient manoeuvres.

Health and Safety

Experimental data and understanding for leaks, releases and ignition to facilitate production of improved guidelines. Additionally, there is no public research on human factors in hydrogen fuel system safety, which is essential given the role of human error in incidents.

7.2 Key Priorities for Industry

Cryogenic hydrogen storage and fuel systems are an essential technology for liquid hydrogen-powered aircraft and some major aerospace companies are actively researching this. Analysis by HCN and its research partners shows the sector needs to accelerate understanding of the fundamental physics and chemistry while addressing the health and safety challenges to enable development of certifiable liquid-hydrogen powered aircraft.

A summary of the industrial technology priorities, translated back to the fundamental research is as follows:

General

Validated modelling approaches are essential for rapid development, evaluation, and improvement of technological solutions. This allows only the most promising options to proceed to avoid unnecessary costly concept demonstration testing. Quick evolution is required from fundamental to systems-based understanding.

Materials

New reliable materials data needs to be generated under standardised conditions to facilitate certification of components and systems. Understanding the behaviour of metallics and composites should extend to manufacturing and assembly impacts on system performance.

Thermofluids

Reliable flow monitoring and fluid management needs clear understanding of hydrogen's thermofluids behaviour, especially near its critical point. The impact of transients and changes in fuel demand signal on fuel systems behaviour should be considered.

Health & Safety

Best practice guides are needed, but these protocols depend on experimental data on hydrogen's behaviour under failure conditions. Health and safety activities require a focus on human factors, ensuring safety from fundamental experiments to large-scale liquid hydrogen handling at airports. Although not highlighted as an immediate industrial priority, experienced practitioners cite this as fundamental to enabling increased use of LH_2.

Professor Julia Sutcliffe, Chief Scientific Adviser, Department for Business and Trade, addresses the HCN Cryogenic Research Conference in January 2025.

7.3 Key Findings and Recommendations for Fundamental Research in the UK

Fundamental research anchors industrial R&D in the UK.

The UK's current strong position within the aerospace industry has been driven by the UK's depth in the fundamental low TRL aerospace research, which has been developed over more than 100 years. The move to cryogenic hydrogen challenges this dominant position, compounded by the fact that countries such as the USA and France have a strong expertise in both aerospace and cryogenics due to their space heritage. This significantly increases the risk of industrial migration of globally mobile organisations who will align their industrial R&D to where these centres of excellence exist, which will have a knock-on impact to UK GDP and high value jobs.

There is a lack of experimental cryogenic data globally.

Timescales for the development of certifiable technologies for hydrogen-powered aircraft are heavily influenced by the ability to create reliable fuel systems which in turn relies on fundamental science, research and knowledge being in place. Without this underpinning knowledge industry cannot rely on data, models and expertise to develop and mature the cryogenic hydrogen storage and fuel system to aerospace certification standards. The global landscaping activity has demonstrated that there is a global deficit in this data, with much of the research being based on a sparse dataset, often over 50 years old, which needs to be addressed for this technology to mature. The UK is significantly behind the USA both in terms of cryogenic expertise and access to liquid hydrogen test facilities for undertaking such research.

Test facilities are needed, and the UK has no space propulsion industry to leverage.

To both fill the global data gap and to build the UK's capabilities such that it can compete with countries with existing cryogenic expertise, open access UK cryogenic test facilities need to be developed. Experimental research is required to fill the data and knowledge gaps highlighted above.

Liquid hydrogen facilities require significant financial investment, so it is necessary to establish where to focus funding to deliver maximum benefit for the UK, not least as there is no space propulsion industry on which to build. Strategic decisions on forming collaborations to deliver open access infrastructure are also required, to leverage existing capabilities in health and safety and measurement standards, to minimise duplication and to ensure the facilities are utilised by many organisations, hence building a critical mass of knowledge in the UK.

There will be a need to develop strategic, international partnerships to supplement the facilities developed, to support rapid growth of the knowledge base and to ensure that investment in facility development targets global gaps, rather than duplicating existing facilities.

To compete with countries with established facilities, the UK needs to build capability at pace.

The development of the UK critical mass in cryogenics needs to happen at pace to bridge the gap with countries with an existing space industry or liquid hydrogen production and storage capability. This demands data and knowledge to be shared, and a structured research approach to minimise duplication and ensure that there are no gaps in critical knowledge. This coordination needs to extend beyond existing industrial-academic collaborations, which have historically been between individual companies and a few collaborators, with broader dissemination limited by industrial Intellectual Property concerns.

A focus on low TRL, pre-normative research, with strong, whole-sector steering will ensure maximum value for money for research outcomes and support development of the supply chain, which is severely lacking for critical components in the fuel system. Such coordination will also leverage learning from related networks including Hy-RES & HIACT and adjacent sectors including marine and low temperature physics.

Rapid transfer of knowledge into industry is best achieved through integrating research across TRL boundaries.

This disruptive technology has highlighted the need for a more integrated approach to funding across the entire TRL landscape, from fundamental through to maturity to ensure that the academic capabilities are developed in line with industrial needs. Countries such as Germany, which has a more integrated approach to technology development, are more successful in taking novel research through to industrialisation and commercial benefits. A relevant example is the spin out of H2FLY[14] from a LuFo funded consortium, comprising DLR and the University of Ulm, H2FLY is now part of Joby Aviation and partnered with Deutsche Aircraft.

To date, where coordination has been required around disruptive or novel technologies, the UK has coordinated across the TRL boundaries, sectors and government departments to deliver a challenge-based approach (e.g. Faraday Battery Challenge, Future Flight Challenge). It is important that a strategic approach to building a critical mass of academic capability, infrastructure and knowledge is adopted to address the fundamental science of cryogenic hydrogen. This should focus on industrial priorities while encouraging academic innovation and research excellence. Failure to adopt a coordinated approach at pace, will see activity become more industry-led which will lead to data being linked to IP rather than openly disseminated.

Overall, for the UK to maintain and build its global position in aerospace in the face of the disruption that LH_2 brings, an independent, industry linked body is required to make strategic infrastructure investment decisions, convene research programmes and ensure rapid knowledge dissemination.

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9. Appendix 1

Research Advisory Board Membership

- *UK-Aerospace Research Consortium*
- *Zero Emissions Aviation – Connected Places Catapult*
- *Health and Safety Executive*
- *DNV*
- *Civil Aviation Authority*
- *UK Hub for Research Challenges in Hydrogen and Alternative Liquid Fuels (HyRes)*
- *Science and Technology Facilities Council (STFC) & British Cryogenics Council (BCC)*
- *The Henry Royce Institute*
- *Rolls-Royce*
- *Airbus*
- *GKN*
- *ZeroAvia*
- *Eaton Aerospace*
- *Spirit AeroSystems*
- *Parker Meggitt*
- *BOC (Linde)*
- *Cranfield Aerospace Solutions*
- *Marshall Aerospace*
- *National Physical Laboratory (NPL)*

Members of the advisory board attend a HCN research workshop.

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