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Hydrogen Capability Network

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Cryogenic Hydrogen Health and Safety

Global Research Landscape

May 2025

About

This report is authored by the University of Nottingham with support from the Health and Safety Executive, in response to the Hydrogen Capability Network's Global Capability Research Tender for the topic of **Fundamental Research into Cryogenic Hydrogen Health and Safety**.

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Prepared with support from the Health and Safety Executive, Science and Research Centre.

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 (HCN)** was launched in April 2023 funded by the Department for Business and Trade, to progress key recommendations from FlyZero which will enable the aerospace sector to deliver liquid hydrogen research and development (R&D).

About the University of Nottingham

The **University of Nottingham** is a Russell group university with an established engineering faculty. The university has a long history of aerospace research and development, and it is ranked in the top ten UK universities for engineering research excellence. The faculty of engineering is the first in the UK to be awarded an Athena Swan Gold Award for advancing gender equality.

Carol Eastwick is a professor of mechanical engineering and the head of the Mechanical and Aerospace Systems Research Group. Her research is focussed on thermofluids and thermal management, particularly involving multiphase flow. The research team behind this report has further expertise in cryogenics, health and safety, and computational modelling.

Disclaimer and Funding Acknowledgement

This work was carried out by the **University of Nottingham** with support from the **Health & Safety Executive (HSE)**, funded by the **Aerospace Technology Institute's Hydrogen Capability Network**.

The report 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.

Cryogenic Hydrogen Health and Safety Summary

The Aerospace Technology Institute's (ATI) FlyZero project concluded that liquid hydrogen (LH2) is the most viable zero-carbon emission fuel for future larger commercial aircraft. The FlyZero reports highlighted technologies which would be required to enable such aircraft to become a reality and the gaps in liquid hydrogen capability. The technological change to a liquid hydrogen architecture is revolutionary and the cryogenic hydrogen storage and fuel system faces great disruption. To get to a certifiable, commercially viable system design it requires a breadth of knowledge relating to cryogenic hydrogen that does not currently exist within the sector. As such, the Hydrogen Capability Network (HCN) has identified three key areas which need to be supported:

- Fundamental research into material behaviour in cryogenic hydrogen environments.
- Fundamental research into cryogenic hydrogen thermofluids behaviour.
- Fundamental research into cryogenic hydrogen health and safety.

Workshops on these three topics were held, to identify subtopics that were of particular interest to both industry and academia. The HCN commissioned global landscaping projects to investigate the current state-of-the-art fundamental research on these subtopics in each of the three key areas, and a report has been written by academic experts on each of them. 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.

This report addresses the health and safety topic. The scope is to document global liquid hydrogen low (1-3) Technology Readiness Level (TRL) health and safety research to identify: global capabilities and work underway, critical research gaps and potential partners for future collaboration.

Publications in low TRL research into liquid hydrogen have been analysed from 1957 to February 2025. The main focus of this report was publications from the last 15 years, to enable current/ active research to be audited and key research groups and facilities identified.

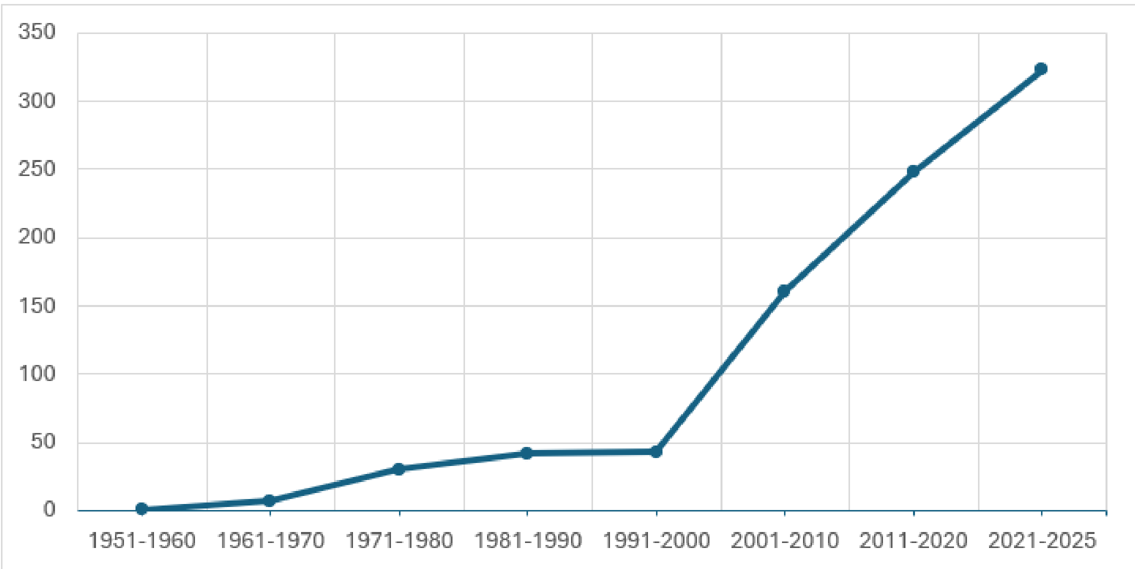

FIGURE 1: LOW TRL RESEARCH PUBLICATION COUNTS IN ENGINEERING LIQUID HYDROGEN SAFETY BY DECADE

Figure 1 shows a timeline of publications into liquid hydrogen engineering safety, indicating a steady increase in research outputs since 2000, with numbers doubling each decade. This rapid increase in activity since 2000 is associated with the strong interest in hydrogen generally over this period in the USA, Japan, Europe and China (Figure 2). In 2009, the HySafe Network of Excellence for the European Commission, became the fully independent International Association for Hydrogen Safety (IA HySafe). This association, along with the establishment of the first International Energy Agency Safety Task (Task 19), catalysed and coordinated activity investigating hydrogen as an alternative energy source across the TRL spectrum.

During 2024 the HCN organised and facilitated a series of workshops to identify what key stakeholders saw as the research gaps for liquid hydrogen that would act as a barrier to its use as a fuel for future aviation. The HCN published the outcomes of each workshop in these reports. The key areas identified within the health and safety workshop report were used to identify the areas of investigation for this global landscaping project. The identified key gaps were combined to form the seven main areas of investigation for this report, these being: leakage, dispersion, ignition, low temperature hazards, human factors, good practice and reports of incidents/accidents. These key areas are included as sections within the report, each section providing an overview, identification of research gaps, details of active research groups, a narrative and key references.

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.

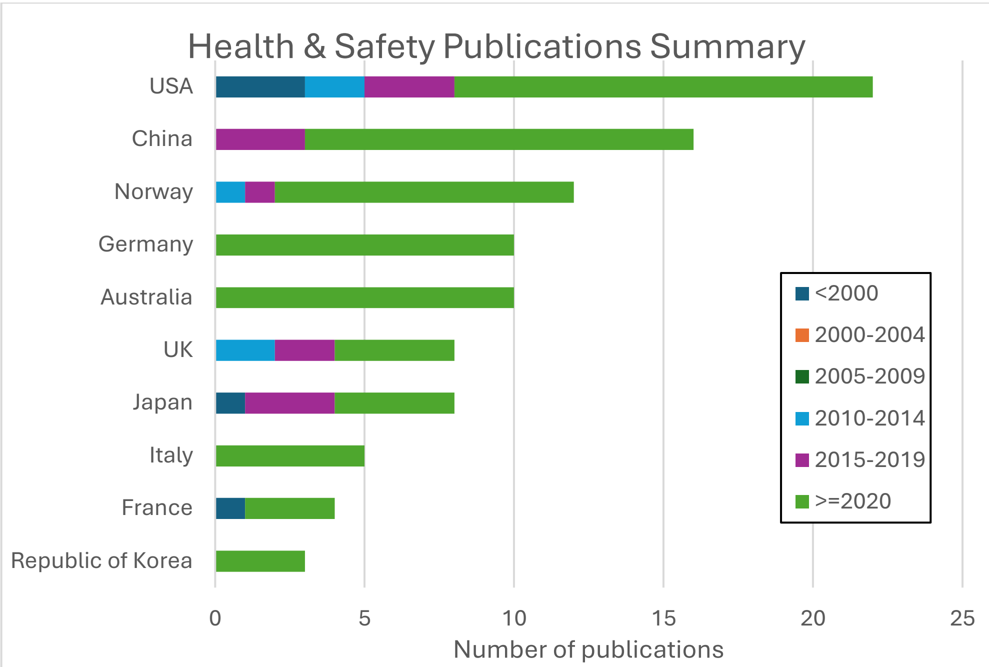

FIGURE 2: LOW TRL RESEARCH PUBLICATION IN ENGINEERING LIQUID HYDROGEN HEALTH AND SAFETY SINCE 2000 SPLIT BY COUNTRY, PUBLICATIONS BY HALF DECADE, FURTHER HIGHLIGHTING THE INCREASE FROM 2020

Key Research Gaps:

- Although a number of countries have liquid hydrogen capability, focused on space applications and similar, only four have capability looking at safety relating to liquid hydrogen as a fuel. These countries were identified from low TRL research leakage publications and are Japan, Republic of Korea, the USA, and the UK. The UK has two sites, Health and Safety Executive (HSE) Science and Research Centre at Buxton and DNV Spadeadam, providing a world leading capability.
- Experimental liquid dispersion data has been generated since the 1950's. However, there are significant gaps in understanding the multiphase behaviour of liquid hydrogen from the leak point through to the far field dispersion of the liquid hydrogen. Six active experimental facilities were identified, across four countries. Those countries are China, Germany, the UK and USA. There were more countries with active research in modelling of dispersion.
- Experimental ignition data, linked to safety, is limited and requires standardisation. Presence of catalytic materials, impurities, dust and humidity, difference in environmental and experimental conditions leads to apparently contradictory results.
- 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.
- Modelling of liquid hydrogen safety is dominated by China with many publications being incremental to each other and generally reliant on experimental validation from other countries.

Key Findings - Tools for Liquid Hydrogen Safety

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 hydrogen and other alternative fuels.

Contents

1. Introduction

The Aerospace Technology Institute's (ATI) FlyZero project concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft. Amongst the many reports published, FlyZero identified a UK gap in liquid hydrogen capability. At the same time, the ATI published the UK aerospace technology strategy, Destination Zero, which identified that the UK could grow its market share from 13% to nearly 18% by 2050, as aircraft fleets transition towards zero-carbon emission technologies.

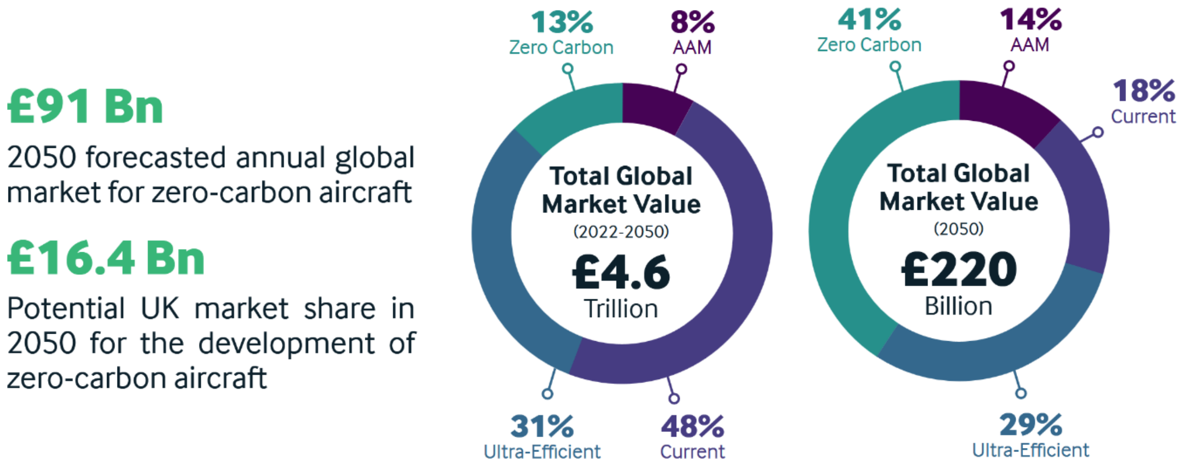

FIGURE 3: ATI PUBLISHED GLOBAL MARKET PROJECTIONS

Although the date for realising this market projection is likely to be later than currently published, the potential opportunity for hydrogen aircraft remains. Achieving this market share is contingent on continued investment in technology development, regulation, and infrastructure. Having identified that other countries are already planning, or have commissioned, facilities and initiatives to support their domestic supply chain, in 2023 the ATI set up the Hydrogen Capability Network (HCN).

The HCN project aims to make recommendations on strategic interventions and what is required to maximise UK industry competitiveness in the emerging liquid hydrogen-powered flight market. Over the past 24 months, the HCN team has connected with over 260 stakeholders from across the UK. This has included 90+ face-to-face discussions and site visits; and over 100 attendees from 44 unique organisations to our testing, research, and skills workshops. The HCN ran a UK Cryogenic Hydrogen Research Conference in January 2025, with over 150 attendees from academia and industry.

1.1. Report Scope

This report was completed for the ATI HCN to provide a global landscaping study documenting Liquid Hydrogen (LH2) low TRL (1-3) research in health and safety. The focus was on research beyond that taking place in the United Kingdom, however where key capability and publications were from the UK these have been included within this report.

There are separate reports to document the global landscapes for cryogenic hydrogen thermofluids and materials.

This report provides summaries of found information relating to low TRL research in liquid hydrogen Health and Safety. Section 1.2 explains the terms (metadata) used while Section 1.3 briefly describes the methodology used. Sections 2 onwards summarise the information found.

1.2. Metadata

The original themes that were defined for health and safety at the beginning of the project were:

- Safety and storage
- Failure scenarios, including from pipe leaks through to catastrophic failure
- Hot and cold Boiling Liquid Expanding Vapour Explosions (BLEVEs) – highlighting key aspects of ongoing research that will impact the aerospace sector

On review by the ATI HCN team and industrial advisory board, these themes above were amended and provided on 15th October 2024 as a secondary metadata set.

- Leakage modelling
- Leakage experimental validation
- Leakage monitoring
- Consequences of leaks (including catastrophic failure)
- Dispersion modelling
- Dispersion experimental validation
- Ignition and flammability modelling
- Ignition and flammability experimental validation
- Low temperature hazards - to human health
- Low temperature hazards-physical phenomena
- Human factors including competency
- Good practice guides (for experimentation/research)

Since many of these more granular titles had a significant overlap with low TRL research outputs, seven general areas were defined to enable the reporting to be more succinct.

These are:

- Liquid Hydrogen Leakage
- Liquid Hydrogen Dispersion
- Liquid Hydrogen Ignition
- Liquid Hydrogen Low Temperature Hazards
- Liquid Hydrogen Human Factors
- Liquid Hydrogen Good Practice Guides
- Health and Safety Incident Databases

The sections from 2 onwards provide reporting under these headings.

1.3. Methodology

Information was collected by using database search engines to pull back publications across 30 different media types including academic journals and conferences, textbooks, reports, patents, datasets and news articles. This information was reviewed, with the content analysed in Sections 2-8 below.

An initial scoping of Health and Safety research publications generated Figure 4, which shows the increase in publications across time from 1950 to the end of 2024. This initial scoping did not include an analysis of publications, it simply returns the publications that met the criteria of liquid hydrogen health and safety low TRL research across the world against year of publication.

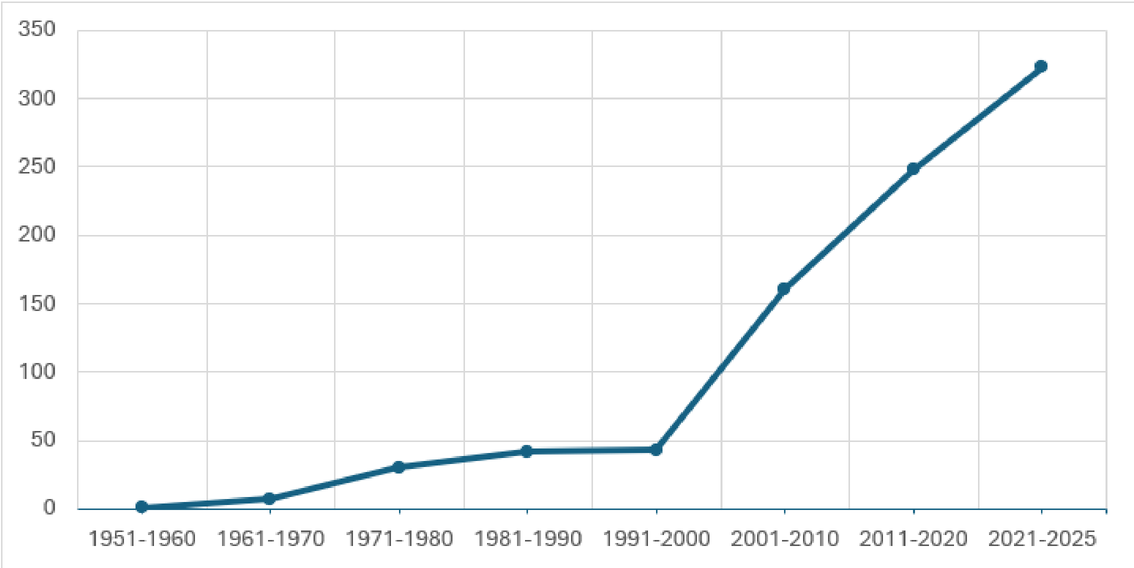

FIGURE 4: LOW TRL RESEARCH PUBLICATION COUNTS IN ENGINEERING LIQUID HYDROGEN SAFETY BY DECADE

The global landscaping review individually assessed papers for their relevance. This enables the split of research to be seen across countries, from 2000 by half decade, showing those that are most active over the recent decade, and this is shown in Figure 5.

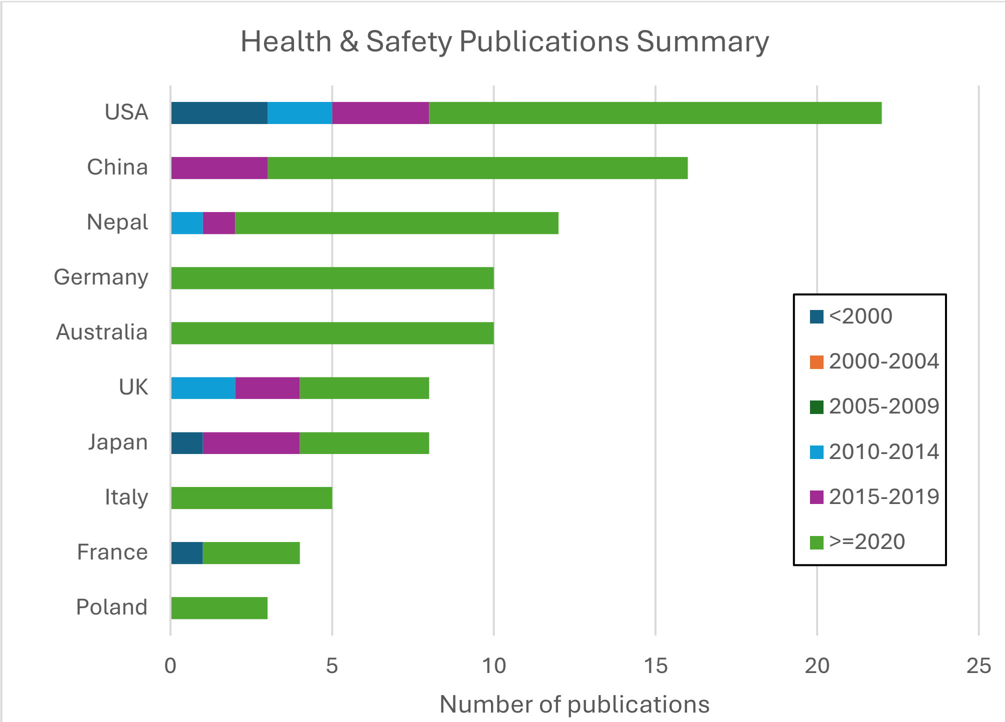

FIGURE 5: LOW TRL RESEARCH PUBLICATION IN ENGINEERING LIQUID HYDROGEN HEALTH AND SAFETY SINCE 2000 SPLIT BY COUNTRY, PUBLICATIONS BY HALF DECADE, FURTHER HIGHLIGHTING THE INCREASE FROM 2020

Figure 5 clearly demonstrates the sustained research from the USA across the time period, as well as the dominance of Europe in the field. Many of the publications from China related to modelling based on published experimental data, although there are some papers that have generated experimental data. This review is based on published information, therefore any research that has not been published due to commercial or security restrictions will not have been assessed within this global landscaping.

2. Liquid Hydrogen Leakage

2.1. Overview

There is significant overlap of research between the leakage and dispersion topics. Within this section, leakage is defined as leaks of liquid hydrogen through cracks or small orifices from a confining vessel/sub-system, linking to near field dispersion. The formation of the crack or orifice is clearly a materials issue, which is not covered here, but is an important aspect covered by other activities within the HCN. This section does not cover processes where liquid hydrogen is interacting with the environment downstream of the leak point or ignition, these are reviewed in Sections 3 and 4.

Leaks from liquid hydrogen systems are a safety scenario that has been investigated through modelling, limited experiments and good practice and incident documentation (the latter two being reviewed within Sections 7 and 8 of this report). Within the Thermofluids report, there are sections on both scenarios and modelling techniques, which overlaps with the content here.

There are a limited number of reported experiments that have been set up for a controlled large-scale release, which are included within the dispersion Section 3 rather than within this section.

Sakamoto [1] investigated the root cause of leakage based accidents in Japan and the USA, identifying incidents via the High Pressure Gas Safety Act Database in Japan, the HIRD database in USA and HIAD Database from the EU. The paper investigated component and materials aspects of leakage causes and is highlighted here to demonstrate the cross-over between thermofluids, Health and Safety and materials considerations.

2.2. Key Research Gaps

- There are only a limited number of experimental publications on liquid hydrogen leakage from cracks or orifices.
- 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.
- There is a lack of consensus in the published information on which tools are most applicable for modelling liquid hydrogen leakage scenarios.
- There is a small amount of research found on liquid hydrogen leakage from moving systems, mainly focused on automotive applications, noting the recent publication of Schiaroli et al, 2025 [2].
- The analytical and theoretical models for Boiling Liquid Expanding Vapour Explosion (BLEVE) underestimate experimental tests performed within SH_2IFT (Research Council of Norway funded project).
- There is a need to compare the consequences of BLEVE with other conventional fuels to ensure that health and safety codes, and regulations, are fit for purpose.
- Experimental data is lacking relating to fragmentation and the size and duration of liquid hydrogen fireballs and radiation from liquid hydrogen fireballs.

- A further issue in relation to liquid hydrogen BLEVE is that there is only one reported incident in the field, which in part is due to the fact that to date, there have been relatively few systems in operation.

2.3. Leakage Narrative

Within this section, a brief description of different leakage scenarios is given to provide greater clarity to the analysis of the literature relating to experimental validation, modelling and consequence of leaks are reviewed.

Abohamzeh et al, 2021 [3] reviews hydrogen safety and classifies the possible concerns of hydrogen handling into seven consequences; gaseous hydrogen leaks, hydrogen jet fire, delayed ignition and explosion, thermal variation, temperature radiation, liquid hydrogen release and Boiling Liquid Expanding Vapour explosion (BLEVE). Ignition related issues are reviewed within Section 4, whilst BLEVE is included in Section 2.6 and Section 5.

Gaseous hydrogen leakage can cause both a flammable mixture (4-75% volume) or an explosive mixture (18-59%) when mixed with air. Where ignition occurs, this can cause a jet fire and this scenario is included within Section 4.

Liquid hydrogen release from a leak can cause a gaseous jet, two phase jet dispersion or cause pooling, with subsequent vaporisation and hydrogen cloud formation. Abohamzeh et al, 2021 [3] further classifies the behaviour as:

a) Flash evaporation
b) Partial or full vaporisation
c) Cryogenic boiling pool formation
d) Air components condensation and freezing

Flash evaporation occurs when liquid hydrogen is exposed to a sudden pressure drop to a pressure below the saturation pressure. The pressure difference from the vessel containing liquid hydrogen and the atmosphere are sufficient to result in an instantaneous vaporisation of saturated liquid hydrogen at the leak point, leading to flash evaporation within the vessel.

Whilst the outcomes of leakage have been defined, there is a lack of data, and often differing outcomes, recorded in the literature. For instance, a liquid hydrogen jet does not always lead to a fireball, nor does a liquid hydrogen pool always exhibit the same behaviour. There are a large number of variables that need to be considered for experimental data collection, with variations in leakage point size and shape leading to different outcomes, which has not been fully explored in the literature. The United States National Renewable Energy Laboratory (NREL) collaborated with the UK Health and Safety Executive (HSE) to produce a set of LH2 releases in 2019 within PRESLHY. This varied both release orientations, height, orifice diameter and pressure, and is reviewed within Section 3, it did not consider leakage from cracks.

Papers have been analysed by region for leakage and Figure 6 below shows this breakdown. This clearly shows the dominance of Europe in publications and this is largely due to key projects such as PRESLHY and ELVHYS. These projects, providing knowledge and funding facilities, means Europe, and in particular the UK, are globally leading in this area.

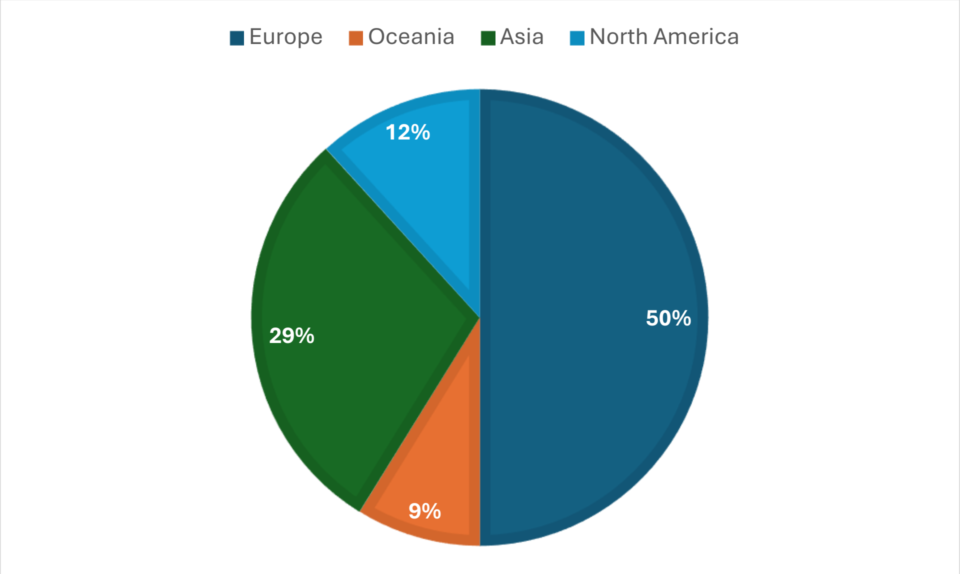

FIGURE 6: RECENT LOW TRL RESEARCH PUBLICATIONS FOR LIQUID HYDROGEN LEAKAGE BY REGION.

2.4. Leakage Experimental Validation

Headlines

- Four experimental test facilities have been identified for liquid hydrogen leak/leakage testing, two of which are within the UK.
- It was noted that tank pressure, temperature and flow rate were controlled as part of the testing protocol. Environmental conditions were noted within publications and have a significant impact on the outcomes.
- Experimental outputs typically measured hydrogen concentrations and temperature measurements at multiple locations relative to the liquid hydrogen leak point.
- Typically, charge coupled device (CCD) cameras were used to observe the hydrogen leak point and cloud.

Kobayashi [4] provides an example of the testing that has been done in Japan investigating leakage and ignition, while Panda & Hecht [5], investigating under expanded jets ignition, is included within Section 4. The paper by Kobayashi [4] provides a review of ignited leakages within the introduction that is helpful in setting the context of the potential formats of leakages and consequences.

It should be noted that whilst this review has focused on global capability, that two of the key identified facilities for experimental testing of leakage are within the UK. These are based at the Health and Safety Executive at Buxton and at DNV Spadeadam. This puts the UK in a world leading position for experimental studies related to Health and Safety scenarios. The papers produced from these groups have formed the core of experimental validation data used in many modelling papers.

Experimental test facilities are included in the table below where there is published information about the facilities, evidencing the ability to test a range of leak scenarios including small orifices, cracks and pipe leak scenarios. Large scale releases are considered in Section 3.

2.4.1. Key Research Groups with Identified Testing Facilities for Leakage Investigations

Institution	Country	Topic
Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science (ISAS)	Japan	Leakage, near field, ignition and far field measurements.
Department of Aerospace Engineering, Inha University	Republic of Korea	Liquid hydrogen clouds.
DNV Spadeadam	UK	Liquid hydrogen releases.
Health and Safety Executive	UK	Liquid hydrogen releases including PRESHLY 2019 set of releases with varying orifice diameter.

2.5. Leakage Modelling Overview

Headlines

- There are a range of modelling tool types available, ranging from system safety and risk assessment, through to high fidelity numerical models of the leak and near field region.
- Whilst directly relevant aviation cases have not been reported in the literature there are a range of scenarios that have commonality, enabling best practice in modelling to be translated.
- The EU projects PRESLHY and ELVHYS provide significant information that is openly accessible.

A review by Abohamzeh [3], provides a review of liquid hydrogen health and safety issues, highlighting modelling tools available for different scenarios, as well as noting sub-model settings. Abohamzeh [3] covers all topics reviewed within this report. The Thermofluids review provides a deeper analysis of available simulation tools.

The PRESLHY project dissemination conference for 2021 provides a range of presentations, including liquid hydrogen releases, although most of these relate to large scale releases.

The majority of leakage modelling works reviewed are from China, whilst validation data is predominantly from USA and Europe.

A range of scenarios (not always in the aerospace context) have been modelled within the literature, with translatable content: -

- Analysis of Liquid Hydrogen leakage from cars in an open area, garage and tunnel scenarios [6].

- Numerical investigation of leaks at refuelling stations [7],[8],[9].
- High pressure leaks from Liquid Hydrogen storage tanks [10].

Across papers, there is an 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. Most modelling papers use commercial computational fluid dynamics tools, whilst some use FLACS, provided by GexCon.

2.5.1. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
School of Engineering, Macquarie University, Sydney,	Australia	1D and CFD modelling studies of leakage.
Xi'an Jiaotong University	China	Dispersion behaviour and safety study of liquid hydrogen leakage under different application situations.
Huazhong University of Science and Technology	China	Numerical investigation of the leakage and explosion scenarios in China's first liquid hydrogen refuelling station.
HYEX Safety AS	Norway	Shows dense gas behaviour in the near range until the hydrogen warms and becomes buoyant.
GexCon AS	Norway	FLACS code CFD computations of liquid hydrogen releases.
Ulster University, HySAFER Centre	UK	Modelling of release, mixing and dispersion of liquid and gaseous hydrogen.

2.6. Consequences of Leaks (Including Catastrophic Failure)

Headlines

- Europe leads globally in low TRL research on consequence of leaks.
- Leakage parameters and local meteorological conditions were found to have consequences on leak outcomes.
- Low TRL research for Boiling Liquid Expanding Vapour Explosion (BLEVE) show differences for prediction outcomes between tools and experimental data.

2.6.1. Overview of Consequences of Leaks

As noted in Section 2.3 Abohamzeh et al, 2021 [3] noted seven consequences of leakage, these being; gaseous hydrogen leaks, hydrogen jet fire, delayed ignition and explosion, thermal radiation, temperature variation, liquid hydrogen release and Boiling Liquid Expanding Vapour Explosion (BLEVE).

Ignited gaseous hydrogen leaks, hydrogen jet fire, and delayed ignition and explosion are reviewed within Section 4; whilst low temperature hazards are included within Section 5.

Where gaseous hydrogen leaks do not ignite, they still pose a Health and Safety risk as a possible asphyxiation risk where leaks are contained within a volume rather than dispersing.

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. During formation of liquid hydrogen pools, heat is absorbed from the atmosphere and substrate (ground or water), which can lead to both freezing of the substrate and a boiling film at the pool/atmosphere surface.

The impact of the liquid hydrogen release on the surrounding temperature can result in formation of solid or liquid nitrogen and oxygen. Baldwin et al, 2021 [11] provide a review of available data and modelling for pool boiling. The majority of modelling publications focus on liquid hydrogen release and rely on a limited set of experimental data, predominantly from the work completed by the UK Health and Safety Executive.

A hydrogen Boiling Liquid Expanding Vapour Explosion (BLEVE) arises where there is a catastrophic rupture of a liquid hydrogen tank.

A BLEVE can occur when there is over-pressurisation of the liquid hydrogen tank due to an impinging fire, where the action of the heat from the fire is two-fold, weakening the tank and pressurising the tank ullage space due to boil off of the liquid hydrogen. This scenario is expected to lead to failure of the tank and a hot BLEVE, the impinging jet fire acting as an ignition source producing a fireball.

Alternatively, a BLEVE can occur when a blocked vent leads to over pressurisation due to the gradual boil off of liquid hydrogen over pressurising the tank. For the case of tank over pressurisation, due to a blocked vent, a cold BLEVE where ignition may not occur leads to a different hazard of a dense, rapidly dispersing multiphase cloud of liquid hydrogen.

In Europe, there has been ongoing research since the 1990's, with more recent projects such as the Safe Hydrogen fuel handling and Use for Efficient Implementation (SH_2IFT and SH2IFT2) project funded by the Research Council of Norway (ENERGIX programme). Collina [12], Ustolin [13] and Ustolin [14] provide publications that highlight the challenges around experimental tests of tank ruptures.

Within the Guidance on Hydrogen Safety Engineering [15], Table 11 details publications considering BLEVE causes and potential prevention and mitigation measures.

There is only one reported incident of a BLEVE in the field, which occurred in 1974, and was referred to within a conference paper by Shen [16]. There have been few failures of this type, which in part is due to the fact that, to date, there have been relatively few systems in operation.

2.6.2. Key Research Groups:

Institution	Country	Topic
School of Energy and Power Engineering, Huazhong University of Science and Technology	China	Numerical investigation of the leakage and explosion scenarios in China's first liquid hydrogen refuelling station.
Bundesanstalt für Materialforschung und – prüfung (BAM) at the Test Site Technical Safety in Horstwalde,	Germany	Exploring experimental tests concerning liquid hydrogen releases.
Bundesanstalt für Materialforschung und – prüfung, Berlin	Germany	SH2IFT Experimental testing - Test Site Technical Safety (TTS) of the Bundesanstalt für Materialforschung und – prüfung (BAM) institute in Germany.
Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Trondheim	Norway	Risk based operational safety SH2IFT.
Liquid Hydrogen Technology Research Center, Korea Institute of Machinery and Materials	Republic of Korea	Part of Research Institute of Carbon-neutral Energy Machinery. https://www.kimm.re.kr/eng/sub020102 Amaral [17].
Health and Safety Executive	UK	https://solutions.hse.gov.uk/about-us/facilities/hse-liquid-hydrogen-testing-facility https://solutions.hse.gov.uk/resources/case-studies#anchor4 https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/gant_mccann_2402045_eu_oecd_hydrogen_webinar_hse_v3pdf
Ulster University, HySAFER Centre	UK	Modelling of storage tank ruptures.

3. Liquid Hydrogen Dispersion

3.1. Overview

Dispersion has been defined here as beyond the near field and where liquid hydrogen is interacting with the environment. The previous section summarises available information on variation in leak type and near field behaviour, whilst ignition is summarised in Section 4. There is a significant overlap with many papers, Kobayashi et al [18] being an example, of papers that covers all three areas of leakage, dispersion and ignition.

3.2. Key Research Gaps

- Key experimental research gaps were identified in the PRESHLY project, and whilst significant experimental work was undertaken, there remains substantial gaps in understanding the multiphase behaviour of liquid hydrogen from leak point to far field dispersion.
- Whilst there are very recent publications using high fidelity modelling approaches, as well as empirically based low order models, validation is reliant on a sparse data set. This lack of validation data leaves a question on models' accuracy.

3.3. Dispersion Narrative

Release of liquid hydrogen can be instantaneous or continuous, leading to different dispersion behaviours. Typically, an instantaneous release will cause a cloud which rises rapidly within seconds, demonstrating high thermal instability and turbulence. The turbulence within the cloud leads to increased buoyancy, and reduction of hydrogen concentrations within the cloud.

Continuous releases typically form dense clouds, with spill scenarios [19], [20] showing that the velocity of the liquid hydrogen spill had a significant impact on the dispersion of a flammable cloud. Where liquid hydrogen is spilled, the surface it falls onto has a significant impact on the outcome, with past research having considered different materials, as well as spills onto water. As already noted in the consequence of leaks (Section 2.6) the effect of water within the ground freezing and limiting permeation also impacts scenarios, as does the potential for freezing air trapped within the ground.

The dispersion can be differentiated by near-field and far-field. Typically, near-field flows include under-expanded cryogenic jets, with pressure effects leading to localised liquefaction. Far-field demonstrates plume dispersion, with concentration decay matching similarity laws currently used within modelling tools.

Within the PRESHLY project, a state of the art study was undertaken and a Phenomena Identification and Ranking Table, highlighted the physics of liquid releases as requiring further research. These reports highlight that the less well-known phenomena were related to multiphase release of cryogenic materials (flash, rainout, internal flashing, condensation), with heavy to buoyant transient, the most critical to study. The PRESHLY project provided over 200 experimental data sets from Pro-Science/Karlsruhe Institute of Technology (KIT), with the Health and Safety Executive performing 18 large scale release experiments.

Figure 7 shows the regional split for liquid hydrogen low TRL research, showing the dominance of Europe and Asia in recent publications.

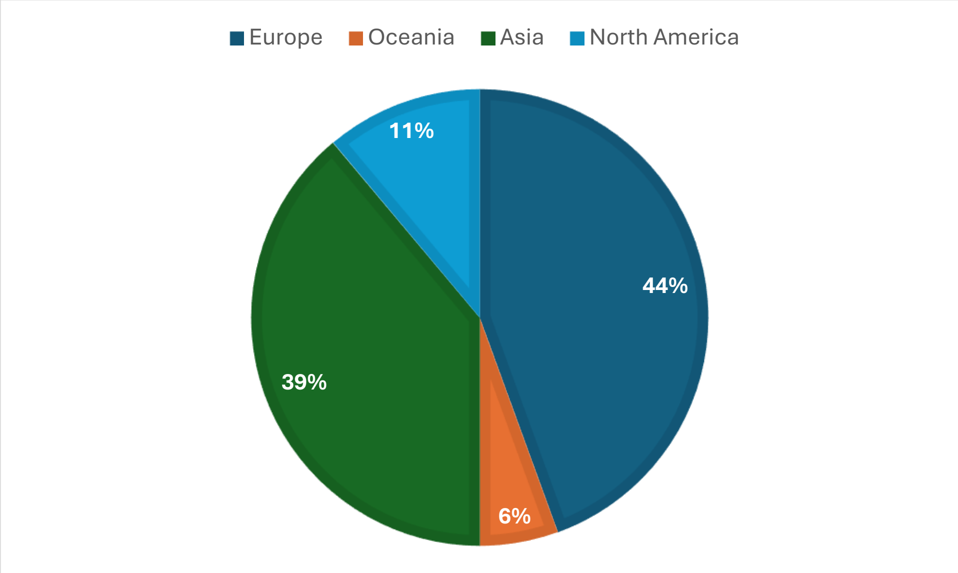

FIGURE 7: RECENT LOW TRL RESEARCH PUBLICATIONS FOR LIQUID HYDROGEN DISPERSION BY REGION.

3.4. Dispersion Experimental Validation

Headlines

- Experimental studies performed between 1950- 2023 have captured temperatures and concentrations downwind of releases of liquid hydrogen. However, these data sets provide only limited validation given the differences in testing scenarios.
- Key questions remain around multiphase cryogenic behaviour and impact on dispersion behaviour.
- Liquid hydrogen dispersion has been compared with liquified natural gas (LNG) releases and liquid nitrogen (LN2) studies within the literature, noting that outflow velocities will be higher. The behaviour of LH2 differs too much from LNG or LN2 for those datasets to be useful in predicting outcomes of LH2 dispersion.
- Spill behaviour is affected by the surface that liquid hydrogen is poured onto (concrete vs cobblestone vs wet/dry sand vs water).

A recent publication by Schiaroli et al, 2025 [2], Table 6, provides an overview of experimental outputs from the 1950's to 2014. These studies consider both small- and large-scale releases, across a range of pressure conditions and both continuous and instantaneous releases.

The most recent experiments are listed from three projects, FFI, PRESLHY and SH2IFT, noting the inclusion of work at the Sandia National Laboratories. Other recent experimental works include publications from Inha University [21], as well as outputs from PRESLHY [22], [23], and Sandia's work [24].

The PRESLHY dissemination conference provides an overview of both experimental and modelling work completed within PRESHLY.

The table in Section 3.4.1 of this report summarises groups with recent publications relating to experimental investigations of dispersion.

3.4.1. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing	China	Experimental work on large volume liquid hydrogen release in open spaces [25].
Pro-Science/Karlsruhe Institute of Technology (KIT)	Germany	Experimental work on cryogenic H2 releases as part of the PRESHLY project Publications – Prenormative Research for Safe Use of Liquid Hydrogen Slides from 2021 dissemination conference.
Department of Aerospace Engineering, Inha University	Republic of Korea	Indoor experimental setup within 4m^3 volume.
DNV (Spadeadam)	UK	Large volume liquid hydrogen releases, PRESHLY advisory board Link to video of presentation hysafe.info/wp-content/uploads/sites/3/2021/05/3_1_Allason_LH2_releases.mp4 Link to slides PowerPoint Presentation.
Health and Safety Executive	UK	Liquid hydrogen releases. PRESLHY partner and ELVHYS EU project - Hydrogen Safety, Liquid Hydrogen Transfer PRESLHY WP3 – rainout experiments PRESLHY workshop, 26-06-2020
NASA Langley Research Centre	USA	Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills.
Sandia National Laboratories & Lawrence Livermore National Laboratories	USA	"Liquid hydrogen spill tests will inform safety standards' technical basis" – news article from April 2024 Liquid hydrogen spill tests will inform safety standards' technical basis : Sandia Energy Links to past publications available at: Hydrogen Safety, Codes, and Standards : Sandia Energy Outdoor experiments performed at Lawrence Livermore National Laboratories liquid hydrogen pad.

3.5. Dispersion Modelling

Headlines

- A range of modelling approaches have been used ranging from commercial CFD codes, bespoke hydrogen codes, to low order modelling approaches.
- Machine learning approaches have been married with CFD in some papers, although validation to experiments is not always included in some papers.
- A significant number of papers use NASA experimental validation data from 1980's rather than data from more recent publications.

There is a significant volume of modelling publications [26], [27], [28], [29], [30], [31] relating to dispersion, although often validation is based on experimental data from two seminal papers from NASA, Langley Research Centre [20], [32]. Whilst there are recent experimental publications the variation in conditions, and level of reporting, is often the reason why modelling studies rely on seminal papers. This reliance on a limited data set is impacting model development and validation. Given the advances in sensor technology since the 1980's a repeat of previous studies would provide a more robust data set for validation. Ensuring that experimental studies report atmospheric and environmental conditions fully would also provide a better validation base for modelling.

3.5.1. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
School of Engineering, Macquarie University, Sydney,	Australia	CFD [9].
The University of Melbourne, Victoria,	Australia	Low order modelling, [29].
Clean Energy Automotive Engineering Centre, Tongji University	China	Dispersion characteristics of large-scale liquid hydrogen spills in a real-world liquid hydrogen refuelling station with various releasing and environmental conditions.
State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing,	China	CFD modelling, predominantly utilising published NASA tests from 1980's.
National Center for Scientific Research Demokritos	Greece	CFD modelling of large-scale liquid hydrogen experiments indoors and outdoors. http://www2.ipta.demokritos.gr/pages/ADREA-HF.html#Basic%20information

Institution	Country	Topic
GexCon AS	Norway	CFD computations of liquid hydrogen releases (FLACS). https://www.gexcon.com/gb/software-industry/hydrogen-gb/
Ulster University, HySAFER Centre	UK	CFD modelling.
Sandia National Laboratories	USA	Comment on website of development of fundamental models Hydrogen Release Behavior : Sandia Energy HyRAM risk assessment is available HyRAM+ : Sandia Energy Hydrogen Safety, Codes, and Standards : Sandia Energy HELPR : Sandia Energy Hydrogen Extremely Low Probability of Rupture (HELPR) is a modular, probabilistic fracture mechanics platform developed to assess the structural integrity of natural gas infrastructure for transmission and distribution of hydrogen natural gas blends.

4. Liquid Hydrogen Ignition

This section summarises low TRL research for ignition relating to accidental releases of liquid hydrogen, and combustion of liquid hydrogen scenarios.

4.1. Overview

Release of liquid hydrogen, via intended or unintended actions, has been considered in both leakage and dispersion (Sections 2 and 3). This section will consider low TRL research on the likelihood of ignition and the impact/consequences, along with approaches to modelling and experimental validation.

Fundamentally, in most situations, ignition can only occur where hydrogen and oxygen are at appropriate concentrations in the gas phase, and coincident with a source of energy to initiate the oxidation reaction and form a flame kernel of critical size such that it can then grow. Auto-ignition can occur where the temperature in the surroundings is sufficiently high, ISO/TR 15916:2015 states a standard value of 584.85 °C. The additional complexity with liquid hydrogen, like liquid sprays or indeed dust clouds, is that extra energy is required to vaporise sufficient liquid H2 from droplets or a pool, to form sufficient H2 vapour/ gas, in addition to compensating for the low temperatures or rapid mixing/ flow. These factors contribute to the inconsistencies observed by workers reported here.

There are multiple points within the ecosystem of liquid hydrogen aviation where ignition is a consideration, these include:

- Transport of liquid hydrogen from production to use site
- Storage of liquid hydrogen at use site, including venting
- Refuelling of aircraft/tank at airport
- Storage on aircraft, including venting
- Combustion chamber within engine – out of scope for this review

There is an overlap with the Thermofluids report where combustion aspects have been reviewed.

Headlines

- There is a clear overlap between leakage, dispersion and ignition publications.
- The European PRESLHY project has provided recent research investigating different ignition scenarios and ignition energy sources.
- The Sandia National Laboratory in USA have investigated ignition and flame characteristics of liquid hydrogen and have an ongoing set of experimental studies relating to generation of standards and codes for large scale leakage scenarios.
- HyRAM+ an open-source risk assessment modelling tool, developed by Sandia National Laboratory, has been used by a number of researchers.
- Discrepancies in experimental outcomes has been highlighted, stressing the need for standardisation of experimental and modelling evaluation, robust regulatory frameworks and utilisation of advanced experimental and modelling techniques.

4.2. Key Research Gaps

- There are a limited number of academic papers that specifically look at ignition associated with liquid hydrogen.
- There are observed differences between reported and practically observed ignition data highlighting the need for standardisation of experimental and modelling evaluation, and robust regulatory frameworks.
- Modelling papers are based on limited experimental publications that are specific to liquid hydrogen. There is data relating to ignition for pools or leakage scenarios, but limited data for ignition from electrostatic or hot surfaces, except for fundamental combustor studies.

4.3. Ignition and Flammability Narrative

There is a large volume of work that has investigated gaseous hydrogen combustion, which is not within scope of this review. A useful resource for understanding this area is the 2023 book by E-A Tingas [33].

Within Europe the PRESLHY project dissemination conference in 2021 had multiple papers reporting investigations of ignition scenarios, this includes those investigating electrostatic discharge [34], ignition relating to pools [35], ignition of cryogenic jet fires [36], and flame propagation which was published as a full paper [37]. Ignition in air, arising from electrostatic discharge, has historically been investigated in High Temperature Plasma Center, The University of Tokyo, Japan (no recent publications), as well as by Sorbonne University (C Proust).

The combustion research facility at Sandia National Laboratory have published a sequence of papers that have looked at ignition and flame characteristics of liquid hydrogen [5] and are currently engaged in assessment of large scale leak scenarios to support US standards, codes and regulations [38]. Simulations of ignition and flames have also been undertaken as one dimensional models [10] and experimentally informed correlations [39] with both international [40] and industrial partners.

The research conducted at Sandia National Laboratories has resulted in a risk assessment tool HyRAM+ being developed, which is available as open-source software. There is a clear overlap between leakage, dispersion and ignition publications in this area.

There is a very recent paper [41] that highlights the discrepancies between hydrogen ignition data reported in literature, and that obtained from practical observations of ignition data (ignition temperatures, minimum ignition energies and flammability limits), including a review of those relating to liquid hydrogen. The paper notes potential reasons for these discrepancies relating to practical real-world applications (presence of catalytic materials, impurities, dust and humidity) as well as differences in environmental and experimental conditions for the available ignition data in literature. The conclusion highlights the need for standardisation of experimental and modelling evaluation, robust regulatory frameworks and utilisation of advanced experimental and modelling techniques.

The research that has specifically investigated combustion of cryogenic hydrogen, not related to accidental releases, is limited. There is a large body of research on modelling liquid fuel droplets, but few relate to hydrogen. Chen et al, 2018 [42] , Min et al. 2020 [43] and Lv et al, 2025 [44] provide examples of modelling work on cryogenic hydrogen, highlighting the lack of validation data available. These publications were all produced by the same group, School of Astronautics, Beihang University, China.

Figure 8 shows the low TRL research publication split across regions, as in other sections of this review Europe and Asia dominate the recent openly published research.

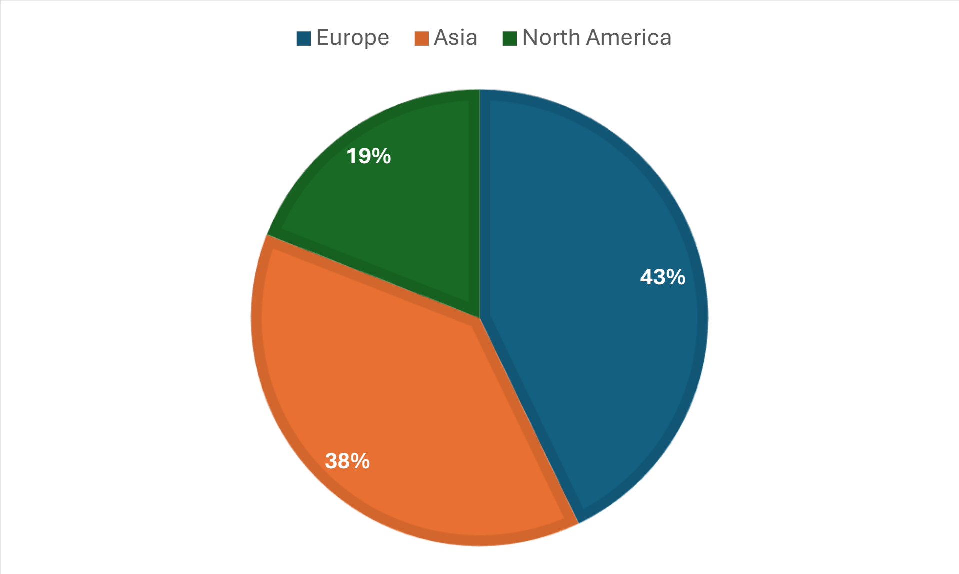

FIGURE 8: RECENT LOW TRL RESEARCH PUBLICATIONS FOR LIQUID HYDROGEN IGNITION BY REGION.

4.4. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
Institute of Thermal Science and Technology (Institute for Advanced Technology), Shandong University, Jinan	China	Collaboration with Sandia, processing of experimental data to remove noise.
School of Astronautics, Beihang University, Beijing	China.	Simulation of combustion, latest publication utilising https://www.cantera.org/

Institution	Country	Topic
Institut National de l'Environnement Industriel et des Risques, Parc Technologique ALATA, Sorbonne University, Laboratory TIMR, UTC/ESCOM, Centre Pierre Guillaumat	France	Experimental ignition tests, electrical/capacitive.
Karlsruhe Institute of Technology	Germany	PRESLHY outputs, pool evaporation and fires, flame propagation.
Pro-Science	Germany	PRESLHY outputs, pool evaporation and fires.
Health and Safety Executive	UK	PRESLHY output Electrostatic charge density evaluation.
Ulster University, HySAFER Centre	UK	Modelling Ignition of hydrogen-air mixtures, including at cryogenic temperatures, for minimum ignition energy.
Combustion Research Facility, Sandia National Laboratory	USA	Experimental, jet flames: https://crf.sandia.gov/research/hydrogen/ https://crf.sandia.gov/research/experimental-capabilities/integrated-test-capabilities/laser-diagnostics-for-cryogenic-gas-releases/ Risk Assessment Models: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/
Mary Kay O'Connor Process Safety Center (MKOPSC), Artie McFerrin Department of Chemical Engineering, Texas A&M University	USA	Very recent publication reviewing ignition data, no specific H2 research reported on website. Research

5. Liquid Hydrogen Low Temperature Hazards

5.1. Overview

Liquid hydrogen hazards were investigated both experimentally and theoretically in the literature reviewed. The work mostly focussed on physical phenomena and included topics such as rapid pressure changes due to sloshing or boil-off, rapid phase transitions (RPT), hydrogen Boiling Liquid Expanding Vapour Explosion (BLEVE), electrostatic charge of liquid hydrogen, safe removal of frozen air from vacuum/insulation spaces around tanks and explosion of hydrogen storage and transfer equipment.

Headlines

- Whilst Rapid Phase Transitions (RPT) during liquid hydrogen spills on water was reported to be a minor issue, ignition of the resulting hydrogen-air cloud, in the absence of an obvious ignition source, was a significant concern.
- Electrostatic charge, relating to both storage and pipe transmission, highlighted as a potential risk.
- While BoilFAST and SINDA FLUINT software were used to model pressurisation in storage tanks, there were no works found explaining why this specific software are better than other commercially available or open source CFD software.
- BLEVE from storage tanks are hazards that are being investigated by multiple research groups, notably as part of SH2IFT project.

5.2. Key Research Gaps

- As already noted in Section 2.6, the analytical and theoretical models for Boiling Liquid Expanding Vapour Explosion (BLEVE) underestimate experimental tests performed within SH_2IFT (Research Council of Norway funded project).
- The potential for a liquid fuel to generate an electrostatic charge during refuelling is well documented and for kerosene there are both safety standards and additives used to manage this risk. The data for the flow of liquid hydrogen and generation of electrostatic charge is limited. Models often use hydrocarbon data to validate against due to the lack of experimental data.
- There is lack of research on how low temperature liquid hydrogen hazards affect human health.

5.3. Low Temperature Hazards Narrative

Low temperature hazards with liquid hydrogen is a topic that has a significant volume of research published.

Hazards due to the low temperature of liquid hydrogen include:

- Electrostatic charge generation due to flow over wall surfaces of pipes is a potential hazard, it can cause a spark discharge, a source of ignition.

- Solid or liquid air forming on cold external surfaces for a liquid hydrogen system, providing a source of oxidant close to the system, but also causing low temperature handling issues including cold burn hazards.
- Solidification of air when liquid hydrogen leaks or spills, with a consequent detonation or ignition consequence.
- Vaporised liquid hydrogen will cause a low temperature vapour cloud which can be denser than air and act as a dense gas cloud.
- Contact between liquid hydrogen and a hotter liquid can trigger a Rapid Phase Transition (RPT) explosion.
- As oxygen has a higher melting and boiling point than nitrogen, there is the potential for oxygen to condense faster when air is solidified. When a storage system is cycled in temperature, and the solidified air melts, it is possible that there will be a higher concentration of oxygen present, providing a higher risk for ignition.

Liu et al. [45] provides one recent example of papers that have studied electrostatic characteristics of liquid hydrogen in tanks and pipe flow, for both static and dynamic filling conditions. This area is more fully reviewed within the Thermofluids report. The generation of electrostatic charge is a risk for all dielectric liquid flows within pipe systems and may provide a spark discharge, a potential energy source for ignition. As liquid hydrogen has both low electrical conductivity and a low minimum ignition energy this provides a risk for any liquid hydrogen flows through pipework, including fuelling an aircraft. Lui et al. [45] developed and validated a model for the generation of electrostatic charge for liquid hydrogen. However, validation was not against liquid hydrogen, but hydrocarbons, highlighting a lack of experimental data for liquid hydrogen. It should also be noted that the dielectric constant for liquid hydrogen is based on data taken between 1960-1990; fundamental properties in the Thermofluids report provides more information on the dielectric constant.

Odsæter et al. [46] performed numerical analysis of accidental liquid hydrogen spillage on water, based on previous liquid natural gas spills. They assessed the triggering of rapid phase transitions (RPT) and concluded that an RPT, as a consequence of a spill on water, was an issue of minor concern. However, Tamburini et al, [47] reported experimental tests of liquid hydrogen onto, or into, water found that whilst RPT was not observed self-ignition did occur, with blast wave overpressure and heat radiation, despite there not being an ignition source apparent. Hall et al. [48] performed experiments on ignited spills of liquid hydrogen to determine parameters such as flammability limits of a liquid hydrogen vapour cloud, flame speeds through a liquid hydrogen vapour cloud and subsequent radiative heat levels after ignition, while Panda [5] experimentally investigated the ignition and flame characteristics of under expanded jets.

Storage tanks for liquid hydrogen may see leakage of air into vacuum or insulation layers. Where this occurs air will solidify, causing both a pressure and temperature rise in the insulation layer. Where there is a rise in temperature this can cause the air to melt and liquid air to pass through the insulation region, reaching the inner tank, and potentially triggering a fracture. Krenn et al. [49] used SINDA/FLUINT software to build a thermal model to simulate frozen air in the annulus whilst Krenn et al [50] extends this work to provide safe methods for removal of air.

Ustolin et al. [14] and Collina et al. [12] undertook experimental work to study the consequences of catastrophic rupture of a double walled vacuum-insulated liquid hydrogen tank. While Ustolin et al. [13] performed theoretical and analytical studies to assess the consequences of BLEVE due to rupture of liquid hydrogen tanks. These models were then validated with the experimental results provided by the BMW car manufacturer safety tests conducted during the 1990's.

Figure 9 indicates, that for low TRL research on low temperature hazards, there is a more even split by geographical region than other areas of health and safety research.

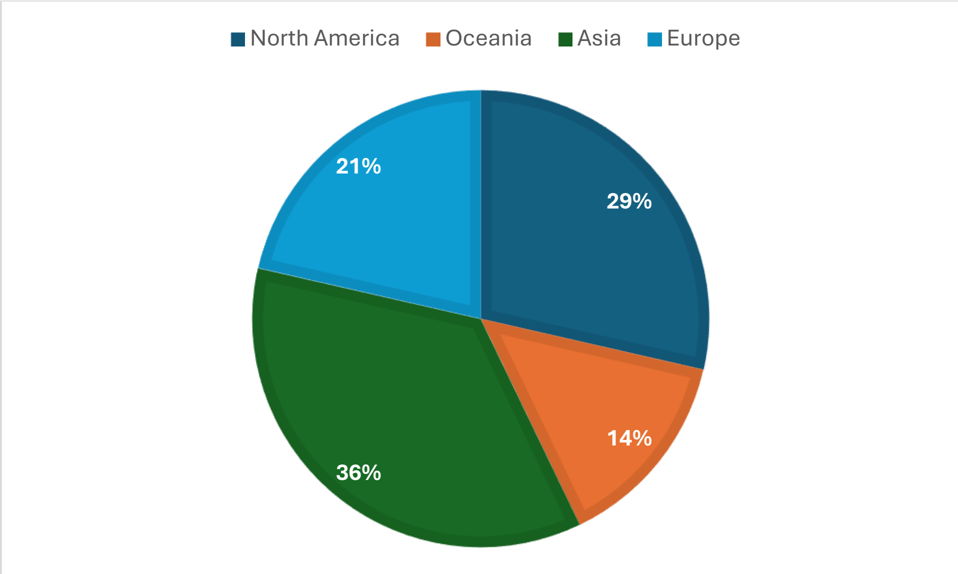

FIGURE 9: RECENT LOW TRL RESEARCH PUBLICATIONS FOR LIQUID HYDROGEN LOW TEMPERATURE HAZARDS BY REGION.

5.4. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100028, China	China	Numerical investigations of combustible clouds and cold effect clouds movement in far field. Uses HSE data for validation.
Bundesanstalt für Materialforschung und – Prüfung, Berlin,	Germany	BLEVE tests under SH2IFT programme.
SINTEF	Norway	Liquid hydrogen spills on water—risk and consequences of rapid phase transition.
DNV	Norway	Flashing, pooling, frost formation.
NTNU	Norway	Consequences of liquid hydrogen tank explosions, BLEVE.

Institution	Country	Topic
Institute of Advanced Sciences, Yokohama National University	Japan	Social risk approach for assessing public safety of large-scale hydrogen systems.
NASA Kennedy Space Center FL	USA	The safe removal of frozen air from the annulus of a liquid hydrogen storage tank.

6. Liquid Hydrogen Human Factors

Headlines

- No human factors research relating to liquid hydrogen was visible in the open literature. There are publications that include the words human factors, but the content relates to risk assessments.
- Literature on quantitative risk assessment (QRA), and risk assessment were visible for liquid hydrogen.
- QRA tools such as the HyRAM algorithm and HyRAM+ software identified, also included within Section 7.

6.1. Overview

There are multiple publications around risk assessment methods for liquid hydrogen, but there were no human factors publications specific to liquid hydrogen that were visible within the open literature.

However, there are human factors papers relating to gaseous hydrogen (Bulat et al, 2024) [51] for liquified natural gas (LNG) (Tubis et al, 2022) [52] and for gaseous hydrogen at point of refuelling (Chauhan et al, 2024) [9].

Since there was no visible human factor research relating to liquid hydrogen, literature on human factors relating to aviation was reviewed. The Human Factors Analysis and Classification System (HFACS) was originally developed for the aviation industry and has been translated to other sectors. HFACS has developed to the point that there are textbooks written for the aviation sector [53],[54]. Although this research area is active [55], there are no publications relating to the use of liquid hydrogen.

There are recent papers on risk assessment methods for liquid hydrogen [56],[57].

Groth developed HyRAM whilst based at Sandia National Laboratories, which is a software toolkit that assesses safety in the use, delivery and storage infrastructure of hydrogen.
https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/

6.2. Key Research Gaps

- There is no open literature on human factors applied to liquid hydrogen. Whilst there are quantitative risk assessments in the open literature, there is no evidence of specific human factors research.

6.3. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
Systems Risk and Reliability Analysis Lab (SyRRA), Center for Risk and Reliability, University of Maryland	USA	Critical review and analysis of hydrogen safety data collection tools https://crr.umd.edu/research https://crr.umd.edu/clark/faculty/807/Katrina-Groth developed DOE HyRAM toolkit hyram.sandia.gov
University of Salerno	Italy	Research is focused around fire risks and includes liquid hydrogen road transport. https://docenti.unisa.it/001911/en/curriculum

7. Liquid Hydrogen Good Practice Guides

7.1. Overview

This section provides links to information around health and safety good practice that are openly available. While the outputs provided here are not low TRL research publications, they have often been created as an output from research studies. The key outputs are linked in the table below in Section 7.3.

Headlines

- Documents highlighted below within the table focus on proactive hydrogen safety through reliability engineering, quantitative risk assessment (QRA), and knowledge exchange.
- QRA tools such as the HyRAM algorithm and HyRAM+ software identified.
- Four tools have been identified that collect hydrogen system safety data, listed in Section 8. These are H2Tools Lessons Learned, Hydrogen Incidents and Accidents Database (HIAD), National Renewable Energy Lab's (NREL) Composite Data Products (CDPs), and the Centre for Hydrogen Safety (CHS) Equipment and Component Failure Rate Data Submission Form.
- The IEA Task 43 "Safety and Regulatory Aspects of Emerging Large Scale Hydrogen Energy Applications" is developing research to feed into Industry guidance, regulations, codes and standards. This is still underway.

7.2. Good Practice Guides Narrative

A horizon 2020 project ENABLEH2 generated best-practice safety guidelines for handling and using liquid hydrogen in aircraft and at airports. However, this work does not appear to be available in the open literature.

Wen, et al, [58] provides an overview of safety data, including experimental test data available for different accident scenarios for liquid hydrogen. Bunkering data is reviewed, with a conclusion that there are some substrates that need to be addressed for bunkering real-world application. However, the specific substrates are not listed.

Brenan et al, [59] describes a European hydrogen "train the trainer" framework for responders, HyResponder, with responders across 10 European countries being trained in hydrogen safety. The teaching material was made available in 8 languages, with a new operational training platform for responders extended to include virtual reality-based training. Link listed in table in Section 7.3 below.

Groth et al [60] reported on IEA task 43, a study to review current knowledge gaps in the safety practices for liquid hydrogen. West et al [61] specifically looks at the needs for quantitative risk assessment and concludes that there is a lack of specific reliability data for hydrogen.

The Clean Hydrogen Joint Undertaking has published a good practice guide on Hydrogen safety in engineering while Class NK has published Guidelines for Liquefied Hydrogen Carriers (Edition 3.0).

7.3. Key Research Groups with Recent Publication Activity

Institution	Country	Topic
PRESLHY Horizon 2020 Project	Europe	Chapter on liquid hydrogen safety published 31/3/2021. https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
EIGA - European Industrial Gases Association	Europe	Safety in storage, handling and distribution of liquid hydrogen, 2019. https://www.eiga.eu/uploads/documents/DOC006.pdf
DLR	Germany	European hydrogen train the trainer framework for responders: Outcomes of the HyResponder project. https://hyresponder.eu/wp-content/uploads/2023/05/L5_HyResponder_Level4_230220.pdf
Physikalisch-Technische Bundesanstalt (PTB) National Metrology Institute	Germany	Report on impact of para and ortho hydrogen on flow measurement best practice, including practical example of required amount of catalyst. https://oar.ptb.de/resources/show/10.7795/110.20221115
ClassNK	Japan	Guidelines for liquefied hydrogen carriers (Edition 3.0) maritime behind paywall. https://www.classnk.or.jp/hp/en/hp_pressrelease.aspx?id=12202&layout=1
SINTEF	Norway	Metrology for hydrogen vehicles – Gaseous Hydrogen. https://www.sintef.no/projectweb/metrohyve-2/ https://www.sintef.no/globalassets/projectweb/metrohyve-2/metrohyve2-a3.3.1-good-practice-guide-final.pdf
Center for Risk and Reliability, University of Maryland	USA	Critical review and analysis of hydrogen safety data collection tools https://crr.umd.edu/research
H2 Hydrogen Tools	USA	Collection of best practice guides covering all areas of hydrogen, including Gaseous (GH2) and Liquid Hydrogen (LH2) Fuelling Stations. https://h2tools.org/bestpractices/best-practices-overview

Institution	Country	Topic
NREL	USA	Overview of international activities in hydrogen system safety in IEA Hydrogen TCP Task 43. https://www.ieahydrogen.org/task/task-43-safety-and-rcs-of-large-scale-hydrogen-energy-applications/

8. Health and Safety Incident Databases

The list below details some links to health and safety incident databases. The databases are not low TRL research but have been included for completeness within this report.

It should be flagged that the databases accessed by the links below are not specific to liquid hydrogen but provide detail on accidents or incidents, with information on dealing with safety issues arising from hydrogen.

- Hydrogen Accidents and Incidents Database – HIAD EU
  https://data.jrc.ec.europa.eu/collection/id-00295

  European Commission, Joint Research Centre (JRC) (2023): HIAD 2.1. European Commission, Joint Research Centre (JRC) [Dataset]
  PID: http://data.europa.eu/89h/1d6b06e9-3a89-4ec2-b051-3fb8a28eab9f

  Melideo, D., Weidner Ronnefeld, E., Dolci, F. and Moretto, P., HIAD - Hydrogen Incident and Accident Database, In: 53rd ESReDA Seminar, 14-15 November 2017, Ispra, 53rd ESReDA Seminar, 2017, p. 326-336, JRC108666.https://publications.jrc.ec.europa.eu/repository/handle/JRC108666

- H2 tools provides an overview training and safety information for hydrogen. It is provided by the US government and is maintained by the Pacifici Northwest National Laboratory, funding by DOE office of Energy Efficient and Renewable Energy's Hydrogen and Fuel Cell Technologies Office
  https://h2tools.org/
  Hydrogen safety incident examples
  https://h2tools.org/sites/default/files/Hydrogen_Incident_Examples.pdf

  H2Tools Hydrogen Safety Bibliographic Database https://h2tools.org/bibliography

  Lessons learned https://h2tools.org/lessons

  https://h2tools.org/sites/default/files/Doc6_02SafetyLiquidHydrogen.pdf

- Liquid hydrogen HyResponder https://hyresponder.eu/consortium/
  2023 https://hyresponder.eu/wp-content/uploads/2023/05/L5_HyResponder_Level4_230220.pdf

9. Conclusion

This report has reviewed recent low TRL research for health and safety of liquid hydrogen globally. There is a clear increase in publications since 2000, with research being seen across all continents in the last 10 years in particular. However, there are still significant low TRL research gaps that will impact the adoption of liquid hydrogen as a fuel. Throughout the report those research gaps have been highlighted under specific topics, below they are summarised in full.

9.1. Identified Low TRL Research Gaps for Health and Safety of Liquid Hydrogen

- There are only a limited number of experimental publications on liquid hydrogen leakage from cracks or orifices.
- 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.
- There is a lack of consensus in the published information on which tools are most applicable for modelling liquid hydrogen leakage scenarios.
- There is a small amount of research found on liquid hydrogen leakage from moving systems, mainly focused on automotive applications, noting the recent publication of Schiaroli et al, 2025 [2].
- The analytical and theoretical models for Boiling Liquid Expanding Vapour Explosion (BLEVE) underestimate experimental tests performed within SH_2IFT (Research Council of Norway funded project).
- There is a need to compare the consequences of BLEVE with other conventional fuels to ensure that health and safety codes, and regulations, are fit for purpose.
- Experimental data is lacking relating to fragmentation and the size and duration of liquid hydrogen fireballs and radiation from liquid hydrogen fireballs.
- A further issue in relation to liquid hydrogen BLEVE is that there is only one reported incident in the field, which in part is due to the fact that to date, there have been relatively few systems in operation.
- Key experimental research gaps for liquid hydrogen dispersion were identified in the PRESHLY project, and whilst significant experimental work was undertaken, there remains significant gaps in understanding the multiphase behaviour of liquid hydrogen from leak point to far field dispersion.
- Whilst there are very recent publications using high fidelity modelling approaches for liquid hydrogen dispersion, as well as empirically based low order models, validation is reliant on a sparse data set. This lack of validation data leaves a question on models' accuracy.
- There are a limited number of academic papers that specifically look at ignition associated with liquid hydrogen accidental release.
- There are observed differences between reported and practically observed ignition data relating to leak scenarios, highlighting the need for standardisation of experimental and modelling evaluation, and robust regulatory frameworks.

- Modelling papers are based on limited experimental publications that are specific to liquid hydrogen. There is data relating to ignition relating to pools or leakage scenarios, but limited data for ignition from electrostatic or hot surfaces, except for fundamental combustor studies.
- The potential for a liquid fuel to generate an electrostatic charge during refuelling is well documented and for kerosene, there are both safety standards and additives used to manage this risk. The data for the flow of liquid hydrogen and generation of electrostatic charge is limited. Models often use hydrocarbon data to validate against due to the lack of experimental data.
- There is lack of research on how low temperature liquid hydrogen hazards affect human health.
- There is no open literature on human factors applied to liquid hydrogen. Whilst there are quantitative risk assessments in the open literature, there is no evidence of specific human factors research.

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