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AN ANALYSIS OF CIVIL AVIATION INDUSTRY SAFETY NEEDS FOR THE INTRODUCTION OF LIQUID HYDROGEN PROPULSION TECHNOLOGY

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ABSTRACT

Over the next few decades air travel is predicted to grow, with international agencies, manufacturers and governments predicting a considerable increase in aviation use. However, based on current fuel type, International Civil Aviation Organization (ICAO) project emissions from aviation are estimated to be seven to ten times higher in 2050 than in 1990. These conflicting needs are problematic and have led to the EU Flightpath 2050 targeting dramatic emissions reductions for the sector (75% CO2, 90% NOX by 2050).

One proposed solution, decreasing carbon emissions without stunting the increase in air travel, is hydrogen propulsion; a technology with clear environmental benefits. However, enabling the safe application of this fuel to aviation systems and industrial infrastructure would be a significant challenge. High-profile catastrophic incidents involving hydrogen, and the flammable and cryogenic nature of liquid hydrogen (LH_2) have led to its reputation as a more dangerous substance than existing or alternative fuels. But, where they are used (in industry, transport, energy), with sufficient protocols, hydrogen can have a similar level of safety to other fuels. A knowledge of hazards, risks and the management of these becomes key to the integration of any new technology.

Using assessments, and a gap analysis approach, this paper examines the civil aviation industry requirements, from a safety perspective, for the introduction of LH_2 fuel use. Specific proposed technology assessments are used to analyze incident likelihood, consequence impact, and ease of remediation for hazards in LH_2 systems, and a gap analysis approach is utilized to identify if existing data is sufficient for reliable technology safety assessment. Outstanding industry needs are exposed by both examining challenges that have been identified in transport and industrial areas, and by identifying the gaps in current knowledge that are preventing credible assessment, reliable comparison to other fuels and the development of engineering systems.

This paper demonstrates that while hydrogen can be a safe and environmentally friendly fuel option, a significant amount of work is required for the implementation of LH_2 technology from a mass market perspective.

INTRODUCTION

The increase in economic growth and prosperity worldwide, especially in the developing nations, has resulted in a steady increase in the use of air travel. In the 27 years before 2010 personal world air transport is reported to have increased by 5.9% per year [1]. In January 2017 the International Civil Aviation Organization (ICAO) indicated the number of passengers reached 3.7 billion in 2016, a 6.0 per cent increase over the previous year [2]. The UK government estimates that demand for air travel from UK airports will rise between 1% and 3% every year until 2050 [3], Airbus estimates that growth of air travel will increase by 4.5% each year until 2035, requiring 33,000 new passenger aircraft [4], and International Air Transport Association (IATA) estimates that worldwide air travel will double between 2015 and 2035 [5].

This growth has caused many to have concerns in relation to the environmental effects of kerosene based world-wide transport. Aviation is a significant contributor to the emission of greenhouse gases (GHGs). These are gases that have been identified as contributing to rising global temperatures such as carbon dioxide (CO_2), and nitrogen oxides (NOx). To address this, a number of regulatory and industry groups have issued mandates. IATA has issued a global commercial aviation mandate to reduce net CO_2 to 50% of 2005 levels by 2050 with carbon neutral growth from 2020 [6].

There is a general industry appreciation that a major step change will be required to produce the next generation of aircraft capable of providing the future required aviation service and further efficiencies while also factoring in environmental challenges.

A number of novel ‘game-changing’ technologies have been proposed including distributed propulsion systems, boundary layer ingestion, the use of cryogenic fuels (cryofuels) and the use of superconductors for electrical distribution and electrical propulsion.

The use of cryogenic fuels is a complex proposition that would require large scale aircraft design, processes and infrastructure changes. The production, transport, ground storage, refueling, on-board storage and the cooling/ combustion systems will all require new engineering solutions and supporting safety processes.

This work will cover these suggested technologies on an aircraft, focusing on their associated hazards. It will also identify the knowledge gaps that will need to be addressed to be able to fully assess the technology use safely.

Hydrogen Gas propulsion in aviation

Hydrogen gas has been explored for propulsion use in aerospace since before the Second World War. It is commonly used for propulsion in spacecraft (in combination with LOX) and is the fuel of choice (or part of the hybrid systems) for many of the proposed projects currently in development such as SpaceX, Skylon and SABRE and the EC ENABLEH2 project.

Hydrogen is desirable in principle primarily because of its high heat of combustion, however its low density means significant space is required for on-board storage and the existing storage solutions have a significant weight penalty [7]. Usefully, hydrogen has a high specific heat capacity relative to kerosene meaning it can be used to as a coolant for the turbine etc., improving the efficiency of the system.

While there have been recent papers looking at the conversion of existing engines, development of new engines and modelling of hydrogen combustion in those engine, few of those aircraft-focused studies have paid specific attention to the safety of those systems, both in terms of their lab use, and their integration into the wider aircraft industry. However, a wider body of work has been built on liquid and gaseous hydrogen safety in wider industries such as transport and energy. The following section will summarize the state of the art on hydrogen safety knowledge.

HYDROGEN HAZARDS & SAFETY MANAGEMENT

There are a range of hazards that must be assessed and dealt with to make technology using cryofluids safe. The main areas to consider are physical hazards associated with temperature and pressure changes and chemical hazards associated with flammable events etc.

Low temperature hazards for cryogenic fluids

The primary issues associated with cryogenic fluids are low temperature hazards. The primary issue for user safety is that of cryogenic burns (frostbite), but risk from asphyxiation must also be considered. In relation to system safety, the cold fluid can cause solidification of contaminants, and blockages (solidified air), so systems should be sealed from external contamination. The cold system surfaces can also result in oxygen enrichment of air nearby, which is of particular concern in the case of leaking flammable fluids. Cold surfaces can accumulate solidified gases that subsequently melt and drip liquefied components of air, creating a hazard in that area.

There is also an additional problem in relation to the leak of cryogenic flammable materials. Although generally vaporization is expected in the case of LH_2, if leaked for a period of time, it can cool the ground enough to cause pooling and to cause and oxygen enriched hydrogen ‘snow’ that would provide significant fire hazards. These issues should also be considered around the supply chain, including in the creation and storage of cryogenic liquids.

A leak of cryogenic fluid could potentially cause issues with onboard systems by cooling components (such as electronics) to below their minimum operating temperature.

Pressure/ Expansion hazards for cryogenic fluids

According to Molkov [8] there are significant hazards related to any system reliant on maintaining pressure and or low temperatures in relation to thermal expansion, boil-off, and pressure/ temperature maintenance and control .

Care should be taken with any fuel to understand and monitor liquid-to-gas expansion ratios, overpressure hazard sources, overpressure hazard sources, pressurization/ cooling system failure, pressure relief system failure and fire hazards. Much of these properties are well understood as the cryofuels are all commonly used and stored in industry [9].

Particular attention should be taken to define how the effects of changing pressures and temperatures in a relatively short space of time (flight profile) affect the storage and behavior of the cryofuels, and the effect of the continual repeated changes required for aerospace. The repeated thermal expansion and contraction could create fatigue issues for LH_2tanks.

LH_2 volume expands with heat significantly more than water (coefficient of thermal expansion at normal boiling point is 23 times that of water at ambient conditions). Thermal expansion and contraction create problems for storage systems e.g. fatigue, unwanted stresses, propensity for leakage. The behavior of any two-phase flows formed can be modelled but models have not been properly validated due to a lack of experimental data.

One safety advantage is that LH_2 releases are visible due to condensing of water/ gases in surrounding environment, although the visible region does not indicate the edge of the flammable zone. The design of cryofuel systems must consider the possibility of contamination from improper purging leading to presence of condensable gases/solidified gas blockages, and contamination by fluids (pressurization gas, pump oils) and organic/ flammable matter from outside the system in enriched, condensed air.

Embrittlement

Low-temperature embrittlement by cryogenic fluids is possible, particularly for containment materials, and materials adjacent to the system. Embrittlement is particularly a risk with cryogenic hydrogen. The mechanical properties, particularly of metals and alloys, can be significantly reduced by exposure to the hydrogen fluid (maximum effect at 200 - 300K). This includes changes in tensile strength, ductility, fracture toughness, and crack behavior. Failures have resulted in the past [9] but this can be avoided by using less susceptible materials. The effect on such materials of prolonged airborne service in the presence of vibration is not clear.

Flammable hazards

In many ways, the greatest safety concern associated with hydrogen fuel is its wide flammability region, relative ease of ignition and explosive power. Flammable hazards in relation to the majority of fuels are relatively well understood. Much work has been done to define the ignitability of hydrogen by flames, heat sources, and mechanical ignition/ sparks [10]. For hydrogen, safe management is essential as hydrogen has a higher laminar flame speed and very low ignition energy when compared to kerosene [11]. The low ignition energy for hydrogen (<0.02mJ) makes stringent ignition source control, and leak control and monitoring, even more important than for kerosene type fuels. Ignition sources (BS EN 1127) should be avoided in regions where hydrogen may leak or collect.

Most recently work has started to better define ignition properties of hydrogen, and hydrogen/methane mixtures, in relation to self-ignition, primarily by adiabatic compression/ shockwave ignition [12] [13] [14], but also charging of hydrogen causing electrostatic [15] and mechanical ignitions [16]. Much work is required to better define the parameters effects especially under variable environmental conditions.

Work has also increasingly looked at medium to large scale ignition experiments [17] [18] [19], and modelling and validation of complex scenarios using computational fluid dynamics [17] [20] but further work is needed to explore this fully on the ground, and in air profile conditions, especially in order to validate modelling. Brewer determines that in a series of large-scale release experiments no evidence of detonation could be found, and that pressure effects from a fireball were negligible when unconfined, however turbulence and obstacles/ geometry may play a key role in worsening this action [19].

Hydrogen leaks easily through very small gaps [21] due to its low viscosity, and is adept at penetrating many solid materials. However, hydrogen has a shorter burn-time and lower thermal radiation if ignited, so the thermal radiation transfer is lower than for Jet-A fuel.

Liquid hydrogen vaporizes rapidly on release, and gaseous hydrogen is relatively buoyant compared with air. Outside these characteristics may be an advantage reducing the chance of a flammable mixture being formed, however internally hydrogen could collect in voids (if not designed out or vented). Hydrogen is invisible to the naked eye (and the majority of visualization methods), however on release of cryogenic LH_2 the immediate condensation of air due to the cold makes the leaks highly visible [18].

From a functional perspective leaks of cryofuels can cause a reduction in volume of external gases, and can create a vacuum that can draw in yet more gas, e.g. oxidizer (air) creating a flammable atmosphere [8]. Boil-off and vent management is also needed for storage both on and off the aircraft. This boil off must be carefully monitored and ventilated to prevent a flammable atmosphere from developing, or the hydrogen must be captured for further use.

Particular attention will need to be paid to refueling technology and processes. The transfer of fuel, and especially cryofuel such as LH_2, creates a particularly dangerous window of time. The transfer is particularly problematic due to the large temperature differences encountered when refueling with fresh LH_2. A liquid hydrogen system design could enable a sealed system, where a flammable mix cannot exist outside of the combustion chamber. Hydrogen leaks (or spills for liquid hydrogen) must be prevented and systems/ environments carefully ventilated and isolated from ignition sources to prevent any fire incidents. In relation to LH_2 Pritchard & Rattigan [21] state the consequences of an accidental spillage or leak are poorly understood, particularly the initial stages of pool spread and vaporization. This will have significant impact on, for example, system design and refueling processes. In relation to aircraft systems/components such as joints, pumps and compressors – both onboard and ground based pumping systems for cryofuels will need careful consideration in terms of their long term reliability, an area that has not been fully addressed for aviation duty. A range of liquid hydrogen technology options for ground-based transport are being explored and introduced [22] and with this work further research is being done to understand the large scale safety implications. NASA is developing a rapid delivery and zero loss storage system, as part of their GODU-LH_2/ GODU-O2 program [22]. Any system must obviously also be designed to prevent operator error.

Modelling of hydrogen using FLACS has been well developed [23] but the understanding of leaks, dispersion and ignition/ fire/ explosion events under varying environmental conditions, particularly for large scale releases, have not been validated to any great degree as only limited experimental work has been performed in this area with specific release rates [19].

When released for a significant period of time (minutes) pooling can occur due to the cooling of the surrounding ground causing a flammable hazard below refueling areas. Additionally an oxygen enriched hydrogen 'snow' can form. The properties of this 'snow' are not well defined and this should be explored to understand how dangerous this material may be, and how prone to ignition [18] [19] [24].

Current safety regulation and guidance

A significant base of research exists on hydrogen use for transport and power [25] [23] [17]. In practice, hydrogen has an excellent safety record compared to hydrocarbon fuels. The safety issues around LH_2 are highlighted by the ANSI/AIAA [26], Beeson [9], Molkov [8], and Pritchard & Rattigan [21]. With safety protocols in place hydrogen is recognized as being as safe as any other fuel, even with some advantages [27] [28] [29] [30] e.g. hydrogen evaporates and disperses faster, has a shorter burn-time and emits less thermal radiation when ignited, and a sealed cryogenic system reduces ignition hazard.

Substantial literature exists on hydrogen hazards and effective ways to characterize, manage and mitigate them in ground-based transport and engineering systems. Several standards for safe use of hydrogen/ flammable gases include:

- ATEX Directives 99/92/EC & 94/9/EC
- ISO TC/97 standards
- NFPA 2 Hydrogen Technologies code
- ANSI/ AIAA Guide to Safety of Hydrogen and Hydrogen Systems G-095-2004
- ASME B31.12 Hydrogen Piping & Pipelines

In Europe work on projects such as Hysafe [31], HyRam [32] as well as FCH JU KnowHy [33] and H2Trust [34] have resulted in analysis tools to assess H2 safety, and comprehensive guidance is used in nuclear environments [35]. Several airports (Heathrow, Berlin, Los Angeles) have introduced H2 fueling stations for ground support/ transport vehicles, thus safety and integration in existing infrastructure have been considered.

A recent report [36] about hydrogen safety, concluded there was confidence the industry could adhere to international safety standards, and the concern had no significant effect on the support for the technology compared with other advantageous factors (e.g. environmental, cost).

However, there are knowledge gaps, particularly in relation to new fuel usage in the aviation industry and the environmental impacts that will need to be addressed in order to develop them for use.

The Cryoplane project [38] explored LH_2 use in aircraft. The project safety tasks identified several major safety areas including bursting discs, lightning strikes, fire protection systems and the effect of bird strike

Kotchourko et al [10] also identified hydrogen safety priorities requiring further research. Relevant to the use of LH_2 for aircraft are:

- The effect of weather and environmental conditions on physical properties, phase changes and heat transfer properties (examining humidity, temperature, wind speed and direction, atmospheric stability class)
- Greater depth on mechanical ignition
- The effect of geometry of system components including pipework, nozzles impact on ignition/ self-ignition
- Flame acceleration and deflagration to detonation (DDT) issues
- Hydrogen releases from existing storage
- Fireball scales, cooling and movement, especially for large clouds

Again, Brewer [38] suggests igniting large releases in order to prevent more serious consequences from an explosion or DDT. The thermal output from a hydrogen ignition is far lower than of a comparable hydrocarbon ignition and thus, it could perhaps be managed more effectively than the worst case scenarios. This needs to be explored as part of the large and smaller scale release/ DDT scenarios.

Recent advances in ground-based hydrogen systems safety and current projects are filling some of these areas of required development however not all gaps have been filled. The following sections will examine risks in a proposed hydrogen propulsion system and the areas of need for further research work.

METHODOLOGY – PHA & GAP ANALYSIS

This section covers the methodology used for the preliminary Hazard List creation, the Preliminary Hazard Analysis, and the follow-on Gap Analysis process.

A Preliminary Hazard Analysis (PHA) is often the first stage of a risk assessment process. It is generally performed at the start of a task, and it can form the basis of later risk assessment methods. The first stage of a PHA (MIL STD 882E) is the formation of a Preliminary Hazard List (PHL); a list of everything that can conceivably go wrong with a system or process.

Two ready-made lists related to aerospace were used as a starting point (Hard et al (2012), Goldberg et al (1994)), but were not regarded as comprehensive. The issues covered in the literature survey in this work added as hazards specific to hydrogen, and its use in aviation (including issues such as cryogenic hazards for LH_2, as well as wide flammability limits, buoyancy, relative lack of a visible flame). The specific scenarios identified in Lowesmith et al, Kotchourko et al, were also added to this process. The PHL process covers both normal conditions (handling of hazardous system entities and ignition sources under expected flight conditions), and off-normal or fault-conditions (i.e. fault of component/system failure, operator error, and other out–of-tolerance issues).

Following the systematic approach of the US DOD, a basic system architecture and division has been proposed (Figure 1) to analyses areas with similar hazard categories. This will form the framework for the hazard assessment. It has been split into 4 sections; 1) LH_2 storage, 2) LH_2 transport, heat exchange and expansion system, and 3) GH_2 transport and heat exchange system, and 4) GH_2 combustion system.

Next an analysis was conducted around each hazard with an emphasis put on any area where the inclusion of hydrogen as a fuel significantly changed design or operational considerations. Each system was assessed for possible PHL hazards. Table 1 shows the rationale employed. Each hazard category has several sub-hazard types, and modes by which these hazards might come about (not an exhaustive list given early stage of design process). This work is a wide assessment of hydrogen hazards in this scenario, without specific system components making organization around category headlines more appropriate than around components. The PHA is used to assess the likelihood and impact of various hazards and whether they could lead to any adverse incidents (Including ICAO annex 13 accidents where serious injury or adverse damage occurs) which affects, or could affect, the safety of operation for an aircraft incorporating a liquid hydrogen propulsion system. The hazards are then also be analyzed to assess their ease of remediation.

Having conducted this PHA process a gap analysis is conducted around each of the hazards/ system items/ areas using an approach similar to that used by the Hanson et al [37] & the US DOE for the nuclear industry. The 'further work required' section of the analysis (Table 1) is performed based on doubts in the risk assessment. Where assessment is difficult due to lack of information/ data, and the safety case cannot be justified to a satisfactory degree, further work is required and the major safety barriers to technology development and uptake, and cross cutting needs for all systems are identified.

Figure 1 A basic possible system architecture for a hydrogen propulsion system proposed in ENABLEH2 project

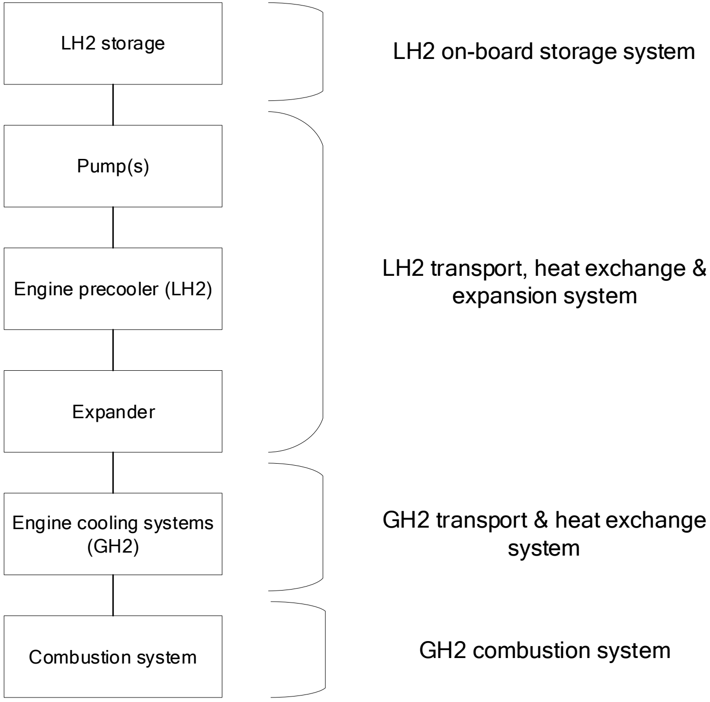

Table 1 Preliminary Hazard Assessment & Gap Analysis framework

Hazard mode number	The number assigned to this system hazard for recall & auditing	1
Hazard category	The broad classification of the hazard	e.g. pressure
Hazard type	The type of hazard associated with that category	e.g. pressure increase
Modes/ info	Possible mode(s) by which the hazard may occur in the system being examined (related to mechanism and components)	e.g. warming from external heat and increased boil off
Outcomes/ notes (separate out)	The resulting negative issues that occur.	e.g. over-pressurisation, tank leak/ breach, cryogenic (cold) damage, potential fire/ explosion.
S1 (1-4)	The unmitigated severity of the outcomes (where 1 is catastrophic and 4 is negligible [a])	1
L1 (A-E)	The unmitigated likelihood of the incident (where A is frequent and E is Improbable [a])	A
Mitigation	The known mitigations that can be performed to reduce severity and/ or likelihood	E.g. Pressure relief devices, hydrogen capture, venting capability
S2 (1-4)	The severity of the mitigated incident outcomes [a]	3?
L2 (A-E)	The likelihood of the mitigated incident [a]	A?
Further work required	Are there areas of doubt, missing data or knowledge gaps that require addressing to enable complete risk assessment	Engineering solutions required, and mechanism info on boil-off in flight profile conditions
References	For decision origin/ audit	EIGA 06/02

? Where doubts exist around the technology solutions or there is lack of data underpinning the decision, a. Severity/ likelihood categories defined in MIL-STD-882E.

RESULTS

The Preliminary hazard assessment activity produced a document of several pages that is difficult to demonstrate in this work. The following section summarizes the findings. Although there was substantial cross-over the main relevant hazard categories and types were identified for each system (Table 2) in relation to specific hydrogen hazards beyond the normal activity of a liquid hydrocarbon fuel aircraft.

All of the major categories listed were applicable for all four of the systems assessed, though to different degrees of likelihood and severity. The hazard type sub-groups for the two liquid hydrogen systems (1 and 2) were largely similar, with some differing modes given the different nature of storage versus a multi component pump, heat exchange and expansion system. The third and fourth system hazards types did not contain the same cryogenic hazards, but were also otherwise similar, with an additional issue of DDT concern in the combustion system. Common themes of containment & structural integrity, ventilation and inerting and preclusion of ignition, and a lack of aviation appropriate information were clear and could be seen in the attempts to remove, alter or mitigate the hazards.

Table 2 Hazard categories and types found to be relevant in hydrogen propulsion preliminary risk analysis process

Hazard category	**Hazard type**	**LH2**		**GH2**	
		S	**TH**	**TH**	**C**
Pressure	Containment failure/ release	x	x	x	x
	Pressure increase	x	x	x	x
Temperature	High temperature	x	x	x	x
	Low temperature	x	x	x	x
Fire	Flammable atmosphere	x	x	x	x
	Fire properties	x	x	x	x
	Ignition source present	x	x	x	x
	Flameout	▨	▨		x
Explosion/ Rupture	Overpressure/ seismic wave	x	x	x	x
	Boiling Liquid Evaporating Vapour Explosion	x			
	Confined Explosion	▨	x	x	x
	Deflagration to detonation	▨	▨	x	x
Mechanical	Impact	x	x	x	x
	Vibration	x	x	x	x
	Strain manoeuvre	x	x	x	x
	Thermal Acoustic Oscillation (TAO)	▨	x		x
	'Fluid hammer'	▨	x	▨	
Chemical	Ortho-para conversion	x	▨	▨	
	Contamination	x	x	▨	
	GH_2 low viscosity	x	x	x	x
	Diffuse/ buoyant	x	x	x	x
	Compatibility	x	x	x	x
Leak/ spill	General leakage	▨	x	x	x
Physiological	Cold burn	x	x	▨	
	Asphyxiation.	x	x	x	x
	Heat Burn	x	x	x	x
Contingency	Fire suppression	x	x	x	x
	Fire fighting	x	x	x	x
	Venting	x	x	x	x
	Purging	x	x	x	x
	Earthquake	x	x	x	x
	Extreme weather	x	x	x	x

x = system is affected by this hazard. LH2 = Liquid hydrogen systems, GH2 = Gaseous hydrogen systems, S = Storage, TH = Transport & heat exchange, C = combustion.

Having conducted the Preliminary Hazard Analysis process a number of knowledge gaps have been identified that require further research work, engineering solutions or further consideration in design. Table 3 contains these by hazard group however the following section details some of the major outstanding issues.

A large number of these issues relate to the new application of a direct hydrogen burning propulsion system to civil aviation. While hydrogen has been used in aviation, and space travel, successfully developing systems that can withstand the rigorous, continual, use, requiring fast turnaround, for civil aviation requires a different level of reliability. Consideration must be given to the impact of take-off, landing, changing flight profile, vibration, strain on storage vessels, and fuel systems (engineering and on-going supporting systems).

Another area where a great deal of consideration is needed is on how to make leaks safe during refueling and throughout flight profile (varying environmental conditions). Internally ventilation, inerting, fire suppression for hydrogen and other fires all need to be considered. Explosion mitigation including tank and system siting, space fillers (such as metal networks), blast walls or vent panels also need to be explored for suitability. All of these issues will have to be considered in the selection of design of storage and system siting. Placement of storage on the wing reduces capacity for escaped fuel to collect, but in a worst-case scenario, such as an explosion, could result in catastrophic wing damage. Placement of tanks inside the fuselage risks collection of fuel and formation of a flammable atmosphere, as well as difficulties in terms of placement (above, below passenger, or even in between cock-pit and passengers have been explored). However, a sealed section could be reinforced and be less susceptible to impact from projectiles, and be more resilient in an emergency landing or crash scenario. Use of materials, particularly composite, though also any materials for system (including cryogenic, and combustor) use will need to be considered. Increased safety may mean increased weight.

The flammability and ignition of hydrogen at altitude are not well understood. The dispersion, and ignition of hydrogen in cold temperatures at low pressure and temperature needs to be better understood, as well as ways to detect these. The jet fire and explosion capability must also be further explored in these conditions.

Accidental release issues would also need to be considered in terms of the larger scale releases that may be possible to the outside refueling environment. Analysis of volume, storage facility location, and precautionary and mitigation methods in case of leaks although this will be the subject of future studies in this work program.

The larger scale issues such as dispersion internally in aircraft or externally at airports during refueling need considerable further research.

In terms of liquid hydrogen systems control and perhaps use of hydrogen boil-off needs to be explored. The reliability of cryogenic systems and the materials that make them up under aviation conditions will again have to be tested. The effect of the ortho-para conversion for liquid hydrogen following liquefaction on the flight systems, ground storage systems and the time that takes will have to be explored.

Finally, in relation to the combustion chamber, the relight ability of fuel to maintain engine, whilst also not risking a detonation is a serious consideration, and the chance of thermo-acoustic damage from hydrogen combustion oscillations needs to be further explored to prevent structural effects.

Table 3 Further areas for research required for safe introduction of hydrogen propulsion derived from gap analysis

Hazard type	**Further work identified to support Liquid Hydrogen propulsion systems**
High pressure containment failure/ inadvertent release	Impact of take-off, landing, changing flight profile, vibration on storage vessels. Consideration to tank siting required for assessing safety impact and mitigations. Further consideration needed to how to make LH_2/ GH_2 leaks/ release safe during refuelling and throughout flight profile (varying environmental conditions)
Increase in internal system pressure	Further work needs to be done to characterise this problem and engineer venting/ inerting solutions for flight operation. Vibration effects require significant consideration. Consideration to tank and system siting required Further work needed to characterise risk from moisture/ freezing causing this problem and to engineer solutions to prevent for flight operation
High temperature/ Heating elements	Further work will be required to examine novel materials (e.g. composite) for safe aircraft use, fuel tank protection and fuel tank insulation - weight being a factor Further work is needed to understand the engineering solutions required, and mechanism of off gassing across flight profile conditions Further work is needed to define hydrogen ignition mechanism and probabilities under flight conditions (range of environmental conditions.
Low temperature	Engineering solutions are required to maintain the integrity of systems under aviation conditions Further work will be needed to define the reliability of materials in cryogenic and cold environment conditions for aviation applications
Flammable atmosphere formation	Further work is required to define flammability of hydrogen across flight profile conditions (flame speed, flammability limits). Further work is needed to understand liquid hydrogen leak dispersion and collection across flight profile conditions. Venting/ inerting tech More research work is needed on large-scale longer-term releases (spillage of large quantity of LH_2 on ground, and water, cloud dispersion of cold hydrogen and ignition, safety distances)
Fire properties	The behaviour of jet fires under aviation/ flight profile conditions needs to be explored more fully.
Deflagration to Detonation (DDT) risk	Further work needed to determine risk of deflagration to detonation involving hydrogen fuel throughout GH_2 systems and risk of shockwave development in combustion system.
Ignition source present	Further work is needed to define ignition probabilities under flight conditions from mechanical impacts/ friction, electrical apparatus, coronal discharge, Radio frequency (at airport given possible loop structure and transmitters). Further work is needed to understand the ignition capability, and engineering requirements to protect LH_2 storage materials from lighting strike This is needed across flight profile conditions. Engineering solutions may be different in different stages of aircraft operation.
Flameout	A specific issue for the combustion system is that of flameout and relight. A flammable cloud of hydrogen reigniting could result in a blast wave, vibration and damage to fuel and other systems, while not relighting could result in worse formation of a larger flammable atmosphere and worse onward effects. Auto-recovery systems including auto-relight systems are therefore required. Various options exist to mitigate this hazard including either stopping shock wave formation by using lean mixture below

	detonable level, ensuring immediate ignition on entry to combustion chamber, avoid geometries that promote flame acceleration/DDT or making systems capable of withstanding a shockwave.
Blast overpressure/ seismic wave	Further work is needed to explore the dangers to aircraft of system explosions in different section of plane, explosion avoidance & mitigation methods, and from a Boiling-Liquid-Evaporating Gas explosion. Work to examine the survivability from fireball ignition, rather than a developing blast wave should be explored.
Confined explosion	Further work is needed to define solutions and mitigations for ignition of leaks. Ventilation, inerting, fire suppression and explosion mitigation, including tank and system siting, space fillers (such as metal networks), blast walls or vent panels also need to be explored for suitability. Tank and system siting will also need considerable thought.
Boiling Liquid Evaporating Vapour Explosion (BLEVE)	The blocking of any pressure relief on storage vessels could result in an overpressurisation leading to a serious explosion, blast wave or possible a BLEVE. Prevention of an explosion is greatly favoured (pressure relief with redundancy and diversity, and prevention of formation of a flammable atmosphere plus exclusion of ignition sources) however, it may be necessary to have explosion venting capability in case of a serious overpressurisation.
Impacts/ collision with protected item	Further work is needed to assess this issue with Liquid Hydrogen in relation to tank isolation, geometry and design in relation to sloshing liquids. Further work is required to define the risk of, and from, events such as loose object impact, acceleration/ deceleration/ gravity, and Fragments/Missiles. E.g. Engine rotors/ fans disks burst and other uncontained engine failure, bird strike
Vibration	Consideration of aircraft motion will need to be considered when adapting existing, and designing all new systems, particularly given the leak-prone nature.
Strain manoeuvre	Consideration of extreme aircraft motion will need to be considered and its impact on hydrogen systems.
Thermo-acoustic vibration	Further work is required to understand the existence and impact of possible thermos-acoustic oscillations
Ortho-para conversion	Impact of this property of LH_2 will need to be assessed in terms of on-board (and other) storage
Contamination	Engineering and design work is required to ensure systems are not contaminated with air which could form a flammable atmosphere, or anything that could result in a blockage.
Fluid compatibility	Further work is needed to understand hydrogen effects on materials embrittlement, and diffusion for LH_2 and GH_2, particularly for new materials. Further work required on composite materials in cold, cryogenic environment and across a varying flight profile temperature. Further work also required to understand leaks or diffusion in systems under pressure.
General leakage to external of system	Further work is needed to define the dispersion and collection of LH_2 and GH_2leaks. Additionally detection methods suitable for use in aviation conditions need to be investigated.
Contingencies: Fire	Further work is required to identify fire suppression capability in aviation for hydrogen flames, or inerting systems, as well as firefighting factors.
Additional consideration	Additional areas for examination for all of these issues are integrity and effects during take-off and landing, changing environmental conditions, vibration, and longevity/ continual use factors associated with civil aviation aircraft.

DISCUSSION

The current state of the art in relation to liquid hydrogen safety and use in aviation has been explored and a theoretical hydrogen propulsion system (proposed as a possible basic architecture in the ENABLEH2 project) examined for risks and hazards. A gap analysis has been conducted to identify key issues (with critical or catastrophic outcomes) and cross cutting issues (affecting multiple systems).

The PHA and gap analysis show that a significant level of research and engineering will be needed to enable the development of a liquid hydrogen propulsion system.

For liquid hydrogen systems a key area for examination is the release of large volumes of Liquid Hydrogen. A great deal of work is still required to fully understand the behavior, dispersion, and pooling abilities of a large liquid hydrogen releases. The true danger is that ignition of these leaks is also not well understood. As safe use and production of LH_2 is becoming accepted in ground-based energy and transport systems, there is now wider acceptance of hydrogen as a future aircraft fuel. Some practical work by Hooker et al (2012) examines some of these issues, but further modelling, and in some cases validation, is needed to be able to reliably predict risks and mitigation/ remedial actions that could enable the use of this material safely at, for example, airports in large volumes.

There are a series of cross-cutting issues that are relevant for all of the system sections examined. The rapid vaporization and dispersion characteristics of potential leaks must be carefully explored and evaluated with suitable visualization or leak detection techniques identified. Engineering solutions exploring venting or inerting will be required where leaks cannot be ruled out. Early detection of minor leaks and cracks would also be necessary before they become serious or fail catastrophically.

The Ignition mechanisms & combustion phenomenon of cryogenic or cold hydrogen across flight profile conditions (e.g. low temperature, low pressure environments) has not been explored to a great degree and needs further exploration. Understanding the risk from static/ corona~~l~~ discharge, lighting and electrical storms and mechanical impacts must be explored further to understand and quantify (probabilistically) the risks. Little consideration appears to have been given to the danger from Radio frequency ignition at airports.

Suitable materials are needed for use in aviation that can withstand a range of conditions (pressure build up, thermal contraction, hydrogen embrittlement, weather) while reliably performing containment of the cryogenic or flammable fuel. As the use of composites increases (e.g. in hydrogen tanks) understanding the behavior and effects will be necessary.

One major cross-cutting issue, and a possible barrier to technology use, is freezing hazard in relation to safety and emergency components (e.g. pressure relief) and it is likely engineering solutions will be required to prevent this hazard.

Mechanical and impact hazards such as the effect of bird strike, uncontained engine failures, and premature failure in vibrating environments will all need to be explored. The danger from sloshing liquids in terms of tank damage is a hazard that does not appear to have been explored.

H_2 is more prone to deflagration to detonation transition (DDT) than most other fuels so the flameout, flood and re-ignition hazards must be assessed as well as the propensity for DDT in the GH_2 systems.

Additionally the different operational modes including take-off, operation across varying environmental conditions of flight profile, safe carry of passengers, staff and cargo, landing, and refueling, as well as vibration effect on systems and use across long time period, for multiple flights, must be considered for each system, and hazard. The majority of this information is not currently available and testing and engineering solutions will be required to address these issues.

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