

Potential risks of developing commercial hydrogen-powered aircraft: lessons learned from individual contributing factors to system failures in hydrogen occurrences

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ABSTRACT

Hydrogen is pivotal to the net-zero roadmap for aviation, offering a sustainable solution to reduce emissions. Currently, there are limited occurrences of Hydrogen-related safety cases within aviation. There have been 222 reported occurrences of Hydrogen-related incidents and/or accidents between 1972 and 2024, sourced from H2Tools. These reports provide valuable insights into potential learning opportunities for the aviation industry as it incorporates early hydrogen infrastructure and operations into its strategy for sustainable aviation. These 222 reports were analysed using Thematic Analysis (TA) methodology, applied with the Human Factors Analysis and Classification System (HFACS) framework to understand commonly occurring failure types and contributing factors. The TA was applied as the study worked with a large secondary dataset of qualitative data, with limited regulation to its content structure. The results revealed that Flow Control Systems were the most common theme of system failures, with a total of 182 (82.0%) occurrences, including 13 accidents, 124 incidents, 40 near misses, and five non-consequences. Furthermore, the theme of Individual Unsafe Acts accounted for 140 (63.1%) of the total occurrences and emerged as the most significant contributing factor across all severity levels, with 12 accidents, 99 incidents, 17 near misses, and 12 non-consequences. Analyses of these key areas can enhance safety standards by targeting events with high frequency of failure and analysing the severity of failure. This can help inform inspection focus, reduce operational risks associated to hydrogen handling in aviation and foster a more resilient environment, capable to adopt hydrogen technologies on a large scale.

Nomenclature

AR	Augmented Reality
CO ₂	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DDT	Deflagration-to-Detonation Transition
EASA	European Union Aviation Safety Agency
H ₂	Gaseous Hydrogen
HFACS	Human Factors Analysis and Classification System
HIAD	Hydrogen Incident and Accident Database
HMD	Head Mounted Display
HUD	Head-Up Display
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IR	Infrared

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LH ₂	Liquid Hydrogen
O&M	Operation and Maintenance
PSIG	Pounds per Square Inch Gauge
SHIPP	System Hazard Identification, Prevention, and Prediction
SMS	Safety Management System
SOP	Standard Operating Procedures

1. Introduction

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to reduce carbon emissions for global

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international flights by 2050 [1]. To achieve this, the industry has been exploring alternative sustainable fuels to kerosene, with hydrogen envisioned as a potential alternative. Hydrogen has been used for many years in various application areas (e.g., aerospace technology, chemical processing, food, and electronic industries) and hydrogen-powered aircraft are predicted to be the least expensive and most sustainable way to fly without CO₂ emissions. Hydrogen-powered aircraft will play a crucial role in achieving the target of a clean sky for net-zero emissions by 2050 [2]; Optimistic assumptions hold that hydrogen-powered aircraft may also be lighter, use less energy, and have lower operating costs than current kerosene-powered aircraft due to hydrogen's higher energy-to-mass ratio [3]. However, using hydrogen as a fuel presents various challenges that must be carefully addressed, as it has a wide flammability range of 4–74% by volume at normal pressure and temperature compared to conventional aviation fuel [4,5].

Considering the safety concerns and risks of hydrogen fuel – new and existing dangers – the industry needs to consider how to best move forward [6]. The current study aims to identify the systemic factors related to hydrogen incident/accident occurrences to recommend mitigation strategies for aviation introduction.

2. Related works

2.1. The importance of lessons learned for developing hydrogen-powered aircraft

Hydrogen in aviation presents numerous safety challenges related to the handling, storage, and utilisation both on the airside and landside of airports. Storing and using hydrogen in a commercial aircraft can be challenging and may cause substantial risk over time. One example of this risk includes the case study for refuelling hydrogen aircraft, which requires increased exclusion zones and non-concurrent aircraft servicing activities [7]. In addition, the clean burn of hydrogen flames makes leaks hard to detect and increases the risk of fire spreading, leading to jet fires or explosions [8]. Consequently, transitioning to a hydrogen economy requires careful planning and thorough risk management within the aviation sector to maintain sufficient safety and achieve public acceptance. This transition requires stricter safety standards and oversight to ensure the safe integration of different hydrogen technologies [9], whereby lessons learned from previous hydrogen accidents/incidents are valuable for enhancing safety risk management (SRM) within the associated aviation, chemical and petrochemical industries.

Developing a hydrogen-powered commercial aircraft presents several safety challenges due to its novel characteristics to the industry (flammability range, low ignition, potential for causing embrittlement, and susceptibility to leakage) and must be considered using existing literature and lessons learned [9,10]. Specifically, the automotive and manufacturing industries have provided well-documented incident and accident reports, with the goal of mitigating or preventing future events of a similar nature, saving time, costs, and lives [10]. There are several open databases that document hydrogen-related accidents, incidents, near-misses, and 'no' events. While some databases provide information about the primary cause of occurrences, many are less comprehensive and do not include recommendations on how to prevent similar incidents from happening again [9,11].

2.2. Emerging technology inducing big challenges to sustainable transport

Hydrogen utilisation has been seen in many industries and practices, from automotive and rail, to aviation and energy production, as it provides a potentially clean energy source with high energy density compared to alternative fuel sources (kerosene, gasoline, and diesel). However, the challenges of hydrogen originate from its high flammability and low minimum ignition properties, which are magnified when hydrogen is liquefied as a cryogenic substance [12]. In comparison to currently used jet fuels, hydrogen has added benefits such as enhancing

engine performance, improved longer range, and having a more favourable impact on availability and the economy [13]. As demand for air transport increases, and is expected to expand more than double by 2040 [14], the need to decarbonise the aviation sector is of concern for its long term sustainability as a transportation sector [15]. Aviation accounts for 11% of all transport emissions which is roughly 3% of global energy-related CO₂ emissions. To be in line with the 1.5 °C goal, decision-makers in both the public and private sectors need to foster a clearer view and firm strategy of what must be done [14,15]. There are two primary forms of hydrogen for industrial utilisation: Liquid hydrogen (LH₂) and gaseous hydrogen (H₂).

Liquid hydrogen can be stored at relatively low pressures compared to gaseous hydrogen storage. As a result, liquid hydrogen has long been considered an appealing fuel for future commercial aircraft [16]. However, the tanks themselves need to be cryogenically insulated to maintain the hydrogen in its liquid state (≈ -253 °C), which adds significant weight and complexity. These issues will need to be addressed in the airframe design of LH₂ aircrafts. Commercial aircraft engines are dependent on high-energy-density fuels due to the mass and volume limitations of jet-engine designs. Alternative fuels like hydrogen will require re-designing of existing engines to accommodate for different physical and combustion properties. Introducing a specific safety management system (SMS) for early hydrogen adoption, tailored to the lessons learned from industry, can proactively inform inspection and maintenance procedures to mitigate the risks of hydrogen.

Part of the SMS is the identification of risk severity through risks assessments, known as Risk Management Systems (RMS). Determining the frequency of failure events can support the identification of the risk severity in operations, as higher frequency events indicate a weakness that needs to be accounted for either through design or human oversight. Developing an SMS for innovative hydrogen-powered aircraft involves a structured approach to ensure safe production, distribution, and usage while adhering to stringent aviation standards [17]. The wide use of liquid hydrogen will require a diverse array of storage and transportation solutions, as airports currently lack the infrastructure for an LH₂ aircraft fuel supply, and there is no existing standardization for the design, construction, implementation, and operation of the entire cryogenic system. Although LH₂ is a clean fuel, there are still some challenges and safety concerns in the aircraft design, refuelling procedures, preventing leakage and maintaining low temperatures [18]. The summaries of the advantages and disadvantages of using LH₂ are shown in Table 1.

2.3. Potential risk associated with hydrogen-powered aircraft

Hydrogen gas is about 14 times lighter than air at ambient temperature, which results in a rapid dispersion of hydrogen gas upwards in a leak scenario (see Table 2). This significantly mitigates the risks posed by the flammability and explosiveness of hydrogen in air. When subject to cryogenic temperature (≈ -253 °C), hydrogen becomes heavier-than-air, resulting in a hydrogen cloud near the ground which can pose a fire or explosion hazard, especially if the area is not well-ventilated and the vapor mixes with air to form a flammable concentration [26]. LH₂ is the most suitable option for aviation applications, given its high gravimetric energy density and low mass density, as well as promoting a cleaner combustion burn than other alternative options. However, the risks of hydrogen should be taken into account when handling or storing liquid hydrogen due to the ease of evaporation. The high burning velocity of hydrogen is between 2.65 m/s and 3.46 m/s, which is significantly higher than methane (0.45 m/s) [7]. It has a high explosive potential, and it is difficult to confine hydrogen flames after explosions [27]. The consequence of inadvertently producing a flammable and explosive mixture with air is the primary risk when working with liquid hydrogen, which has to be managed extremely carefully in the aviation domain. Many occurrences in H2Tools [28] highlighted the hydrogen-related risks documented, including flammability and detonation limits of

Table 1Advantages and disadvantages of applying LH² for future commercial aviation.

Advantages	Disadvantages
Cleaner Burn: Liquid hydrogen produces only water vapor [19].	Low Boiling Point: LH ² tank will need to be better insulated and will require venting for gaseous hydrogen generation [20].
Weight Efficiency: Liquid hydrogen has a higher mass-based energy density than conventional energy carriers [21].	Storage: Liquid hydrogen will require pressurized cryogenic containers for storage, increasing weight and complexity in design [22].
Buoyancy: Liquid hydrogen will be less prominent within the safety zone in the event of leakage, as the temperature rises [3].	Infrastructure: Large scale production, transportation and storage are not available, requiring significant financial investment [7].
Cost-efficiency: Future production and handling of liquid hydrogen is expected to be lower than kerosene fuel alternative [23].	Low volumetric density: Liquid hydrogen has a significantly lower energy density, requiring larger fuel storage for aviation usage [13].
High energy output: Liquid hydrogen contains about 2.5 times the energy per kilogram than kerosene, and is abundant [24].	Flammability: Liquid hydrogen has a significantly higher flammability onset compared to kerosene and is difficult to detect [25].
Extends the engine's lifespan by 25% and lowers maintenance costs because LH ² is a cleaner fuel compared to jet A fuel [18].	Due to the extremely low temperature, all apparatus, such as pipes, tanks, vessels, vents, and valves, must be designed and manufactured to withstand freezing conditions [5].

Table 2

Example of the Thematic Analysis used in the study, based on the phases of thematic analysis identified by Braun & Clarke (2006).

Phase	Description of the process
1. Familiarizing yourself with your data	Transcribing the data from H2Tools into standard formatted documents for familiarisation, reading and re-reading the data with three SME's, and noting down initial ideas for later discussions (3.3.1 Familiarisation with Collected Data for Key Elements)
2. Generating initial codes	Coding interesting features of the data (keywords) in a systematic fashion across the entire dataset, collating data relevant to each code (3.3.2 Coding)
3. Searching for themes	Collating codes into potential themes (contributing factors, equipment involved, and consequences), gathering all data relevant to each potential theme (3.3.3 Generating themes)
4. Reviewing themes	Checking if the themes work in relation to the coded extracts (level 1) and the entire dataset (level 2), generating a thematic 'map' of the analysis (3.3.4 Conceptualization)
5. Defining and naming themes	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme (3.3.4 Conceptualization)
6. Producing the report	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis (3.4 Visualization and Writing Up)

liquid-hydrogen, gas-hydrogen, hydrogen-oxygen, and other hydrogen mixtures, as well as the effect of diluents and inhibitors, ignition sources, autoignition temperature, and the quenching gap in air. However, the calamitous hydrogen explosion at the Fukushima Daiichi nuclear power complex in Japan has evidently shown that there is a shortage of knowledge and lessons learned from previous accidents/incidents [25]. Effective safety management can be achieved only when designers and operational personnel are aware of all hazards related to the handling and use of hydrogen. Much more must be learned on deflagration-to-detonation transition (DDT), storage materials, compatibility with other materials, and chemical properties under

extreme conditions of storage and use [22].

Hydrogen technologies are expected to play a key role in implementing the transition to clean energy systems in future aviation. International collaborations have fostered scientific research for the development of hydrogen production, storage, transportation and consumption. However, compared to current fossil energy sources, hydrogen-powered aircraft introduce different safety management system and regulatory issues that must be understood and addressed [1,11]. There are substantial risks associated with the operation of hydrogen equipment. Most hydrogen hazards stem from the fact that hydrogen is odourless and colourless. Consequently, human senses do not detect leaks of hydrogen. This is why hydrogen sensors are frequently used in industry to detect leaks [25]. To mitigate these risks, a reliable risk analysis methodology is essential for planning appropriate control measures and establishing necessary regulations, which must be structured with the highest standard of safety management systems when dealing with hazardous elements [29]. Previous hydrogen accidents revealed technical failures such as mechanical and pump failures might be interrelated to human error, encompassing staff's lack of readiness in dealing with hydrogen-related equipment during operations or maintenance. These potential failures, either in human performance or system function, can directly or indirectly contribute to accidents and incidents [2]. The method of System Hazard Identification, Prevention, and Prediction (SHIPPP) provides a systematic approach to modelling accidents at hydrogen stations. It can be used to evaluate and predict risks, offering valuable insights for developing risk management strategies to prioritise maintenance, manage change, and implement additional safety measures [29].

2.4. Research objectives

This study analyses past accidents and incident reports between 1972 and 2024 to identify potential risks associated with hydrogen applications across various industries. Learning from these occurrences is crucial in enhancing safety management systems within the aviation sector and aids in developing proactive prevention strategies for designing future hydrogen-powered commercial aircraft, as part of the Clean Sky initiative. To examine possible associations between different contributing factors and system failures, thematic analysis was applied for analysing the data, as it involves creating codes and constructing themes which are "patterns of response or meaning within the data that represent overarching ideas embedded within the larger data set" [30]. Historical hydrogen occurrences often stemmed from an inadequate understanding of hazards (e.g. the Hindenburg disaster and industrial leaks). Comprehensive risk assessments must identify potential failure points in hydrogen production, storage, transportation, and consumption. Thematic analysis offers numerous benefits in combining qualitative and quantitative research, particularly when dealing with complex data. The research objectives for applying thematic analysis in this study are as follows:

To identify the contributing factors of hydrogen occurrences in relation to the severity.

1. To identify the contributing factors, as reported on H2Tools, for hydrogen occurrences in relation to the severity.
2. To identify the equipment failures of hydrogen occurrences in relation to the severity.
3. To investigate the association between contributing and equipment factors from a sociotechnical perspective of hydrogen occurrences.

To develop proactive safety management systems for future hydrogen-powered aircraft.

3. Method

3.1. Sample characteristics

The dataset utilised in this analysis comprised self-reported incident/accident reports from hydrogen usage/mis-usage and subjective outcome findings, sourced from Hydrogen Tools website [28]. H2Tools is designed for public accessibility and is developed and maintained by the Pacific Northwest National Laboratory. The self-reported data is not categorized based on the severity of incident/accident, instead solely documents an incident/accident involving liquid/gaseous hydrogen across varying industry settings such as delivery vehicles, refineries and power plants, seen in Fig. 1 below. The self-reported data is not organizationally required, meaning that reported data is unstructured and varied by nature of subjective datasets. This platform aggregates and optimizes various tools and resources concerning the safety aspects of hydrogen and innovative fuel cell technologies, thereby aiding professionals involved in the design, approval, or utilisation of such systems and facilities, as well as emergency responders. Data cleaning would focus on removing duplicated data and refining the message of the self-reported data, for subsequent analysis. During data filtering, it was determined that the limited data available warranted the inclusion of all reported cases collected for this study, with the exclusion of one duplicated case, as each case reported was a value insight into hydrogen mishandling or associated risk and needed to be considered. In total, 222 cases (spanning from 1972 to 2024) were analysed as secondary data sources, using thematic analysis (TA). In this study, counts of codes and themes are used to indicate the frequency with which specific contributing factors and equipment failures appear across the 222 hydrogen-related occurrences. These frequencies should be interpreted as indicators of reported prevalence in the dataset, rather than as direct

measures of the overall risk associated with each factor. The generation of codes and themes in this study were subjective to three subject matter experts (SMEs) utilised in this study, who leveraged respective experience and expertise within their fields to categorise and analyse the data. These were then discussed in a series of consensus meetings, during which disagreements and differing interpretations were used to refine definitions, merge overlapping codes, and adjust the boundaries of themes. This multi-disciplinary review ensured that the final codebook and thematic structure reflected technical, human, organisational, and operational aspects of hydrogen-related occurrences. As such, the conclusions of the paper are open to variance among other practitioners, however the general association of hydrogen-related risks to specific industry settings is applicable among all evaluators and can be sourced using similar datasets used in this study (see Fig. 2).

Throughout the manuscript, two counting schemes are used: (1) occurrence-level counts, where each hydrogen event ($N = 222$) is counted once per theme regardless of the number of coded elements involved; and (2) element-level counts, where individual contributing factors or system failures are counted separately, allowing multiple coded elements per occurrence. All percentages are reported with their corresponding denominators and subset definitions to avoid ambiguity.

3.2. Theoretical framework for data analysis

Thematic analysis is a research tool used to identify, analyse and interpret the patterns of meaning (“themes”) within a set of data. Themes are conceptualised as patterns of shared meaning across data items, united by a central concept, which is important to the understanding of a phenomenon and is relevant to the research question [31]. Thematic analysis can be applied to explore the factors affecting the processes and consequences of a particular phenomenon, the explicit

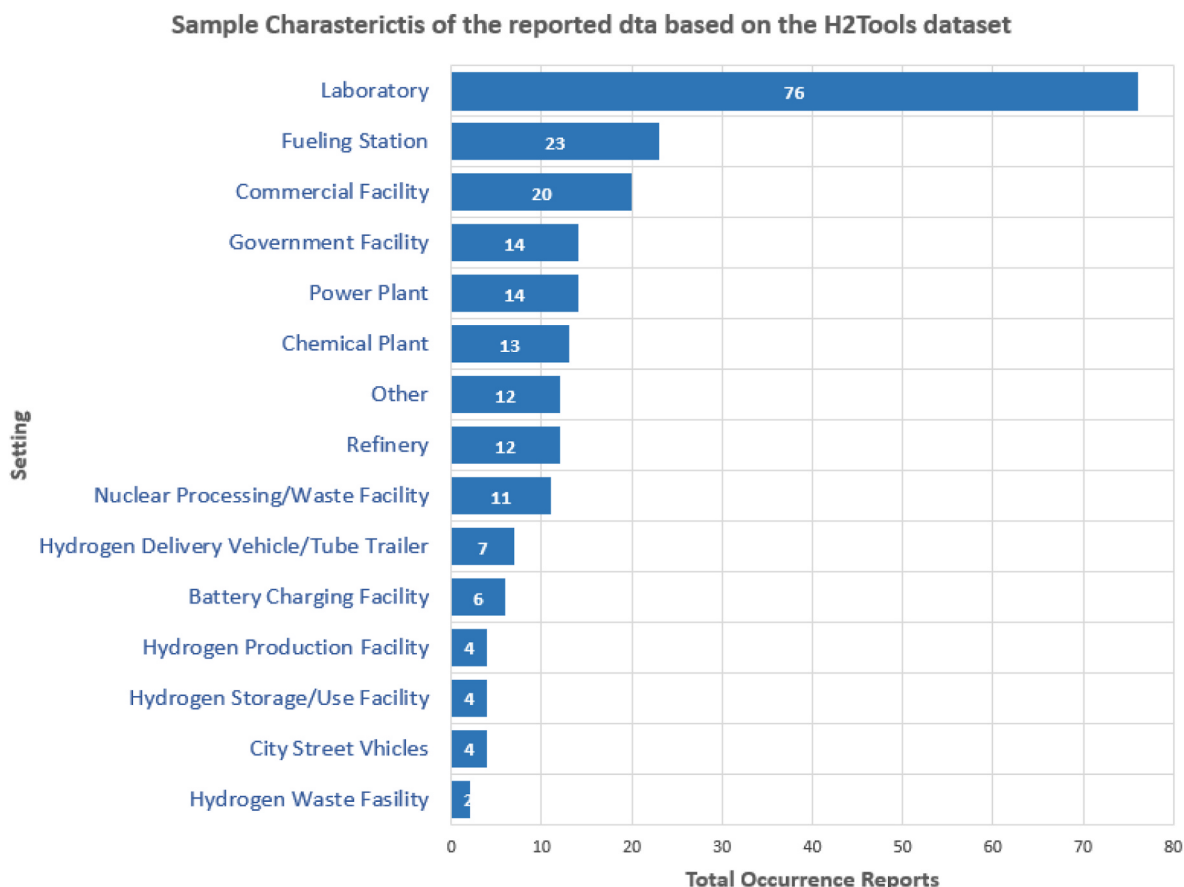


Fig. 1. Sample characteristics of the dataset utilised in the study.

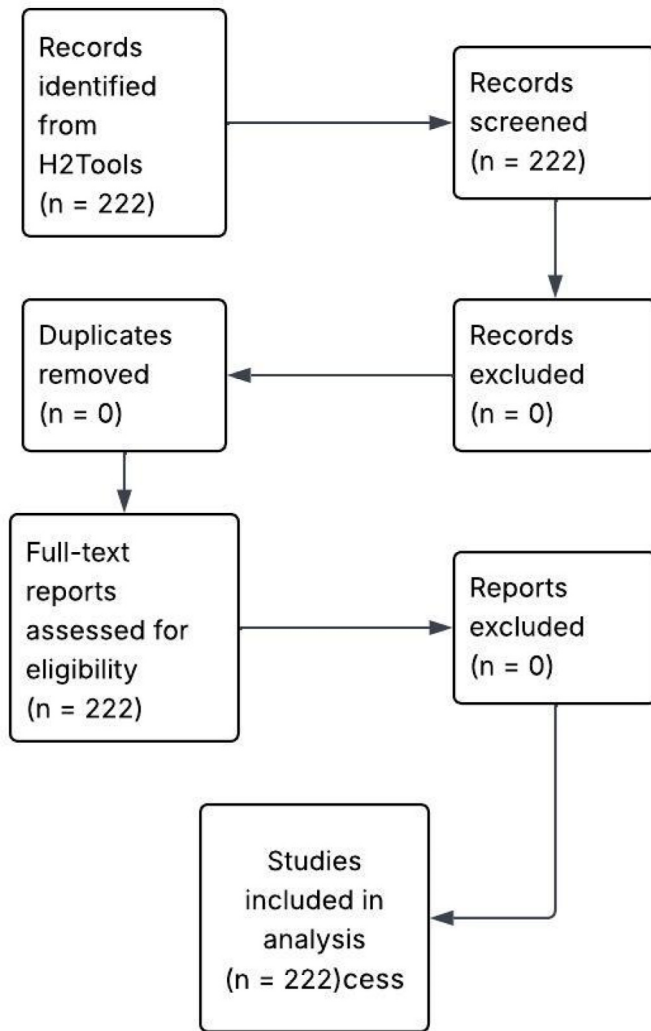


Fig. 2. A PRISMA-style flow diagram document the screening process and record selection.

and implicit standards and 'rules' governing particular practices, as well as the social construction of meaning and the representation of social objects in particular texts and contexts [32]. There is a long tradition of using thematic analysis in phenomenological research, which aims to explore the structure of a phenomenon as accurately as possible based on the subject-matter experts' perceptions, understanding, and experiences as the paramount object of study. It is a constant-comparative method that involves reading and revisiting the transcripts in a systematic way [33]. In Blundell & Harris (2023), TA was used to produce 3-level hierarchy of design requirements for HUD development, using high-level primary themes to represent division of HMD and AR design requirements. Similar work was conducted by Bouamrane et al. (2019) to monitor and support patient treatment plans for chronic kidney disease.

3.3. Thematic analysis

The thematic analysis followed Braun and Clarke's six-phase framework: familiarisation with the dataset through repeated expert review and data cleaning; inductive generation of initial codes; grouping of codes into candidate themes; iterative review and refinement of themes through multidisciplinary consensus; definition and naming of final themes; and systematic reporting using visual analytics and quantitative association testing [30]. This iterative process ensured analytical rigour,

transparency, and consistency across the large qualitative dataset. By combining thematic analysis with the socio-technical framework of Human Factors Analysis and Classification System (HFACS) [34] and subsequent quantitative testing, the method provides a systematic way to extract operationally relevant knowledge from free-text reports for early-stage safety assessment of emerging hydrogen aviation concepts.

Thematic analysis was conducted using a structured, reproducible coding framework with explicitly defined code boundaries and an audit trail from raw report text to final themes. Two complementary counting schemes were employed. Incident-level statistics summarize the prevalence of failure types across unique hydrogen occurrences, with each occurrence counted once regardless of the number of failures involved. Element-level statistics summarize the frequency of individual coded failures and contributing factors, allowing multiple codes to be assigned to a single occurrence. All percentages are reported with explicit denominators corresponding to the relevant analytical level. The secondary data for this research were obtained from the Hydrogen Tools Portal solely for research purposes and were approved by the Cranfield University Research Ethics System (CURES/22560/2024).

3.3.1. Familiarisation with collected data for key elements

The primary goal of this phase was to achieve full immersion with the dataset, thereby facilitating the identification of initial points of interest [35]. To begin the familiarisation process, all 222 reports of hydrogen occurrences were analysed by three SMEs for thorough examination of the factors and different elements involved in each incident/accident. The identification of key elements requires familiarisation with the dataset and recognizing the elements that are relevant to the research question – What are the prudent factors/elements in each reported incident/accident for hydrogen operations across industry (an example of the key elements identified in one report is presented in Table 3). Key elements were categorized as equipment, systems, and/or actions that are captured within a text, which can be further categorized into keywords, as seen in 3.3.2. The SMEs engaged in repeated, careful readings of the reports and lessons learned. During the familiarisation phase, significant effort was dedicated to cleaning the data, which included removing repetitive texts to ensure clarity and focus on subsequent analyses. This data-cleaning process is essential for enhancing the quality and reliability of the analysis to identify key elements (Table 4).

3.3.2. Coding

By thoroughly re-reading the contents of reports, identifying keywords, and organizing them into codes, researchers can structure the analysis in a systematic approach. Following the identification of key elements, the coding process was initiated to reduce the extensive dataset into manageable and meaningful units of analysis. The coding process followed Braun and Clarke's framework [30,36]. The nine

Table 3

One example of familiarisation of occurrence to identify key elements related to the vulnerability of hydrogen equipment during thematic analysis of the dataset.

Synopsis of report	Key elements
In 2024, there was an incident where a small tube trailer hydrogen rupture discs activated prematurely between 1200 and 1500 psig (typically these rupture discs activate @ ~ 3300 psig). The rupture discs exist to protect the storage tubes in the case of an external fire from overpressure and rupture. The trailer had multiple tubes on the chassis. The entire tube trailer emptied through the single rupture disc as the tubes were interconnected. No one was hurt, no equipment was damaged, and no fire resulted. After investigation, it was determined that every storage tube relief device vent piping did not have weather caps on the vent tubes outlets, as required. It was determined that water got into the vent pipes and froze, deforming the rupture disc.	Hydrogen Delivery Vehicle Hydrogen Storage Equipment Hydrogen Tubes Vent Line Vessel Vent Piping Cap Venting System Rupture Discs Relief Device Chassis

Table 4

One example of categorizing key elements into codes related to the vulnerabilities of hydrogen systems during thematic analysis of the dataset.

Key Elements	Codes
Gas cylinder, Hydrogen tubes, Hydrogen Storage Equipment, Dewar, Hydrogen Cryostat, Air-Tight Submersible Battery Case, Battery Storage Container, Atmospheric Storage Tank, Pulp Storage Tank, Sodium Hydride Container, Balloons	Hydrogen Storage Systems

contributing-factor codes and thirteen system-failure codes were developed inductively from the 222 reports [28], using HFACS concepts as a sensitising framework rather than as a fixed coding scheme [34]. This process not only enhances the quality of the analysis but also ensures that the research findings are grounded in a comprehensive understanding of the data's nuances and complexities. The example of distinct code provides a clear framework for understanding the specific types of system vulnerabilities involved in accidents/incidents (Table 4).

3.3.3. Generating themes

Three domain experts collaborated to apply the HFACS framework in a systematic review of hydrogen-related accident/incident reports, familiarizing themselves with the contributing factors and hydrogen equipment involved in these occurrences. This involved reviewing key elements, identifying codes, and developing themes [37]. In qualitative research, a theme serves as a crucial element that bridges research questions and data. It is a conceptual pattern that captures something significant about the data in relation to the research objectives. Themes are derived from the researcher's analytical insights and observations during data collection and analysis [30]. The process of developing themes is deeply rooted in the researcher's own reflections on the data and their understanding of the subject matter.

3.3.4. Conceptualization

By aligning these themes with the research questions and the broader context of the hydrogen industry, insights related to best practices and strategies for mitigating risks for implementing hydrogen-powered aircraft can be offered. During this phase codes and keywords, reflecting the multidimensional nature of contributing factors, were reviewed against the themes to ensure that themes accurately encompassed the various elements associated with hydrogen failure types and modes.

3.4. Visualization and writing up

To visualise conceptualization, heat maps were created to provide a structured framework for understanding the complex interactions within hydrogen systems and help stakeholders understand where immediate attention is required. Although thematic analysis is a qualitative approach to data analysis to identify, analyse, and interpret patterns (themes) using accident/incident reports, it is increasingly being used by researchers to analyse quantitative data as well. In this study, all key elements in the reports were coded as present (1) and absence (0) after being classified by the research team. The dataset consists of a substantial number of categorical variables, related to contributing factors of hydrogen occurrences and system failures which require further analysis. This analysis was conducted using a nonparametric test (chi-square) to determine if the frequency distribution between contributing factors and equipment failure codes differs from the expected frequency. This is supported by tree maps and radar charts for visualizing the dataset and its frequency distribution.

3.5. Quantitative analysis of associations between categories

Thematic analysis provides a structured framework for exploring the full dataset of 222 hydrogen-related occurrences to identify and

interpret recurring patterns within accident and incident reports. Following the identification and consolidation of themes, a chi-square test of association was applied as a post-thematic analytical step to examine relationships between the derived categories. Specifically, the test was used to assess associations between the nine contributing factor codes and the thirteen system failure codes identified through thematic analysis. This quantitative analysis was undertaken to determine whether the observed frequency distributions differed significantly from expected distributions, thereby revealing relational patterns that were not evident prior to thematic coding. To facilitate this analysis, all key elements within the reports were coded as present (1) or absent (0) following classification by the research team, resulting in a dataset comprising multiple categorical variables. The chi-square test was used to complement, rather than replace, the qualitative findings by providing additional analytical insight into the interdependencies between contributing factors and system failures. The results are supported through visualization techniques, including thematic tree maps, and radar charts, which aid in illustrating frequency distributions and highlighting areas requiring particular attention within hydrogen system safety.

4. Result

4.1. Characteristics of key elements related to hydrogen occurrences

There are 222 reports of hydrogen occurrences analysed between 1972 and 2024. The dataset is a comprehensive collection of reports from various settings where hydrogen was utilised or stored, including fuelling stations, power plants, and laboratories. Each setting presents unique challenges and risks associated with hydrogen usage. Multiple codes could be assigned to a single occurrence when several contributing factors or failures were present. The categories of contributing factors are not mutually exclusive due to the interrelated nature of human performance and organisational influences in accident/incident causations. Factors such as human error, situational awareness, decision-making, fatigue, communication, and individual unsafe acts were grouped under the broader domain of Human Factors, while maintaining analytical distinctions between these themes. In this study, human error was specifically defined as individual cognitive failures (i. e., slips, lapses, and mistakes), whereas other factors, including communication and individual operational behaviours, were treated as distinct when broader procedural or organisational processes were evident. Multiple contributing-factor codes can be assigned to a single occurrence; therefore, categories are not mutually exclusive, and each category should be interpreted as the frequency of coded factors rather than disjoint case counts. Upon further examination and cross-referencing with those accident/incident reports, two critical conceptualizations emerged, including (1) contributing factors to different severity of hydrogen occurrence comprising 38 categories and 438 key elements; and (2) equipment failures associated with different severity containing 86 categories and 416 key elements. The most frequently identified theme of contributing factors is the Individual Unsafe Acts, including human error associated with 2 accidents, 36 incidents, 9 near-misses and 5 no events, and situation awareness related to 6 accidents, 37 incidents, 3 near-misses and 4 no events (appendix A). The most frequently identified theme of system failures is the Hydrogen flow controlling systems, including valves associated with 29 incidents and 10 near-misses and piping related to 3 accidents, 28 incidents, and 5 near-misses (appendix B).

4.2. Contributing factors of hydrogen occurrences

In the context of the hydrogen industry, understanding the characteristics of contributing factors associated with occurrences requires a detailed analysis that captures the intricacies of both technological and human factors issues. There are five distinct themes, which contain nine

codes, and 438 key elements have been identified within 222 hydrogen occurrences (Table 5 & Appendix A) described below.

1. **Individual Unsafe Acts:** This theme captures the impact of human errors on incident severity. Unsafe actions by individuals can significantly increase the likelihood and severity of occurrences in hydrogen systems, emphasizing the need for rigorous training and providing safety protocols/manuals.
2. **Organizational Process Issues:** Organizational deficiencies, such as inadequate communication and training, are highlighted in this theme. These issues are critical drivers of incident severity and underscore the importance of a strong safety culture within hydrogen facilities.
3. **Technical Failures:** Equipment malfunctions and design flaws are primary contributors to incidents. This theme emphasizes the need for robust design and regular maintenance of hydrogen equipment to prevent failures.
4. **Operational Breakdowns:** Inefficient procedures and lack of oversight are addressed in this theme. Proper execution of operations is essential to prevent cascading failures that can impact both human safety and infrastructure.
5. **External Influences:** This theme considers external factors, such as environmental conditions or third-party activities, that can exacerbate the severity of incidents. Understanding these influences is crucial for comprehensive risk management.

The contributing factors associated with hydrogen occurrences highlight the complex interplay of human operators, technical designs, standard operating procedures (SOPs) and organizational management issues that impacted the safety of hydrogen delivery, storage and operations. Human error 23.4% (N = 52) and situational awareness 22.5% (N = 50) emerged as the most prevalent factors each accounting for the occurrences. The tree map can reflect the critical weight of these contributing factors to hydrogen safety and underscores the need for enhanced training on human operators' performance and situational awareness to mitigate risks (Fig. 3). The categories of contributing factors are not mutually exclusive due to the interrelated nature of human performance and organisational influences in accident/incident causations. Factors such as human error, situational awareness, decision-making, fatigue, communication, and individual unsafe acts were grouped under the broader domain of Human Factors, while maintaining analytical distinctions between these themes. In this study, human error was specifically defined as individual cognitive failures (i.e., slips, lapses, and mistakes), whereas other factors, including communication and individual operational behaviours, were treated as distinct when broader procedural or organisational processes were evident. Multiple contributing-factor codes can be assigned to a single occurrence; therefore, categories are not mutually exclusive, and each category should be interpreted as the frequency of coded factors rather than disjoint case counts.

4.3. Technical failures in hydrogen occurrences

The analysis of equipment failures among hydrogen occurrences provides critical insights into the weaknesses of hydrogen systems that are essential for improving safety and reliability in both design and operational processes. There are five themes, 13 codes, and 416 key elements involved in 86 unique categories of hydrogen equipment that have been identified in hydrogen occurrences (Table 6 & Appendix B), as described below.

1. **Storage Systems:** This theme focuses on equipment and systems used for safe hydrogen storage. It highlights the importance of preventing leaks and ensuring containment under various conditions to mitigate risks.

Table 5

Summary of qualitative key elements, codes, and themes of contributing factors associated with hydrogen occurrences, with frequency occurrence in brackets.

	Key Elements	Codes	Themes
Contributing Factors	Human Error, Situational Awareness, Decision Making, Fatigue, Individual Action, Accountability, Improper Labelling	Human Factors (140)	Individual Unsafe Acts
	Training Issue, Lack of Protocol/SOP, Incorrect Protocol/SOP, Failure to Follow Procedure, Failure to Follow Standard Operating Procedures, Incomplete O&M procedures, Incomplete O&M procedures, Training Issue	Training and Protocols (81)	Organizational Process Issues
	Communication, Management Planning Deficiency, Inadequate Management of Change, Manufacturer not sure what led to the failure, Lack of Protocol/SOP, Management Planning Deficiency	Communication and Management (74)	
	Change in Procedures, Equipment, or Materials, Deficiency in Procedures, Operation Induced Damage, Abnormal Operations, Incomplete O&M procedures, Improper Purging Procedure, Change in Procedures, Equipment, or Materials	Procedures and Operations (62)	Operational Breakdowns
	Inadequate System Monitoring/Oversight, Lack of Hydrogen Detection Equipment, Monitoring/Oversight	Monitoring and Oversight (48)	
	Flammable Mixture in Confined Area, Weather, Unknown, Abnormal Operations, Laboratory Clutter	Environmental and External Factors (16)	External Influences
	Design Flaw, Equipment Failure, Inadequate venting design, Lack of Hydrogen Detection Equipment, Lack of Component Listing, Material Incompatibility, Improper Purging Procedure	Equipment and Design (13)	Technical Failures
	Software Error, Inadequate System	Software and Technical Issues (3)	
	Inadequate Inspection, Inadequate Maintenance, Equipment Failure, Inadequate Management of Change, Inadequate System Monitoring/Oversight	Inspection and Maintenance (1)	

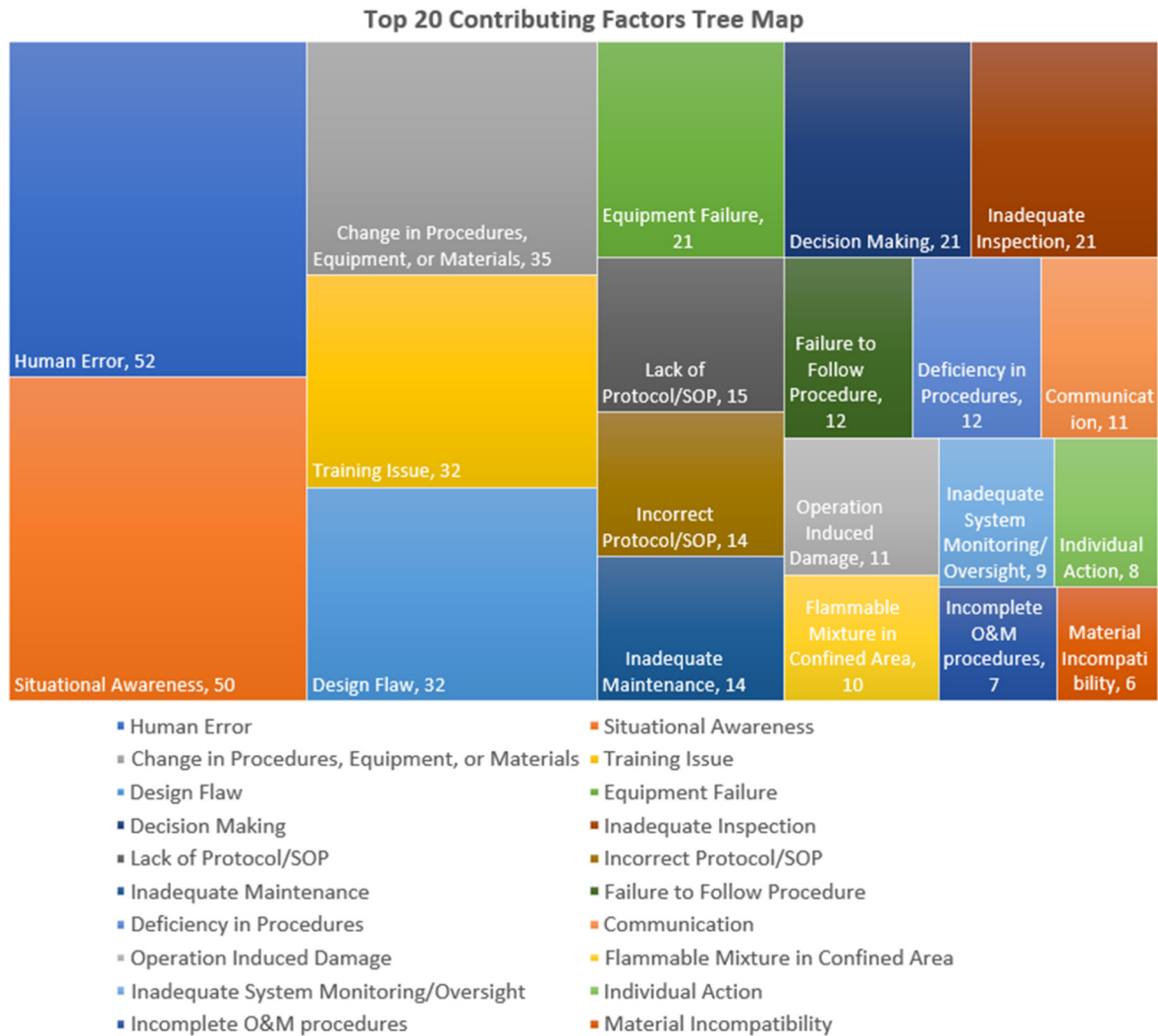


Fig. 3. Tree Map of 20 contributing factor elements, integrating 438 key elements, 9 codes and 5 themes among 222 hydrogen accident/incident occurrences.

- Delivery Systems:** Equipment and systems responsible for the transport and delivery of hydrogen are addressed here. Safe delivery practices are essential to minimize the risk of accidents during transportation.
- Production/Processing Systems:** This newly consolidated theme encompasses facilities and equipment involved in hydrogen production and processing. It reflects the integrated nature of these operations and their significance in ensuring safety and efficiency.
- Flow Control Systems:** Devices used to manage hydrogen flow during production, storage, and delivery are covered in this theme. Effective flow control is vital for maintaining safety and precision in hydrogen systems.
- Safety and Monitoring Systems:** This theme emphasizes systems designed to monitor hydrogen processes and ensure operational safety. Continuous monitoring and adherence to safety procedures are key to preventing incidents.

The results demonstrated that valves and piping issues are the most frequently failing components, accounting for 17.6% (N = 39) and 17.1% (N = 38) of occurrences, respectively. These components are crucial to hydrogen flow controls for production, delivery and storage. The heatmap can reflect the critical weight of the equipment failures associated with hydrogen occurrences in developing interventions and the need for enhanced safety resilience to system failures (Fig. 4).

4.4. Association between contributing factors with system failures in occurrences

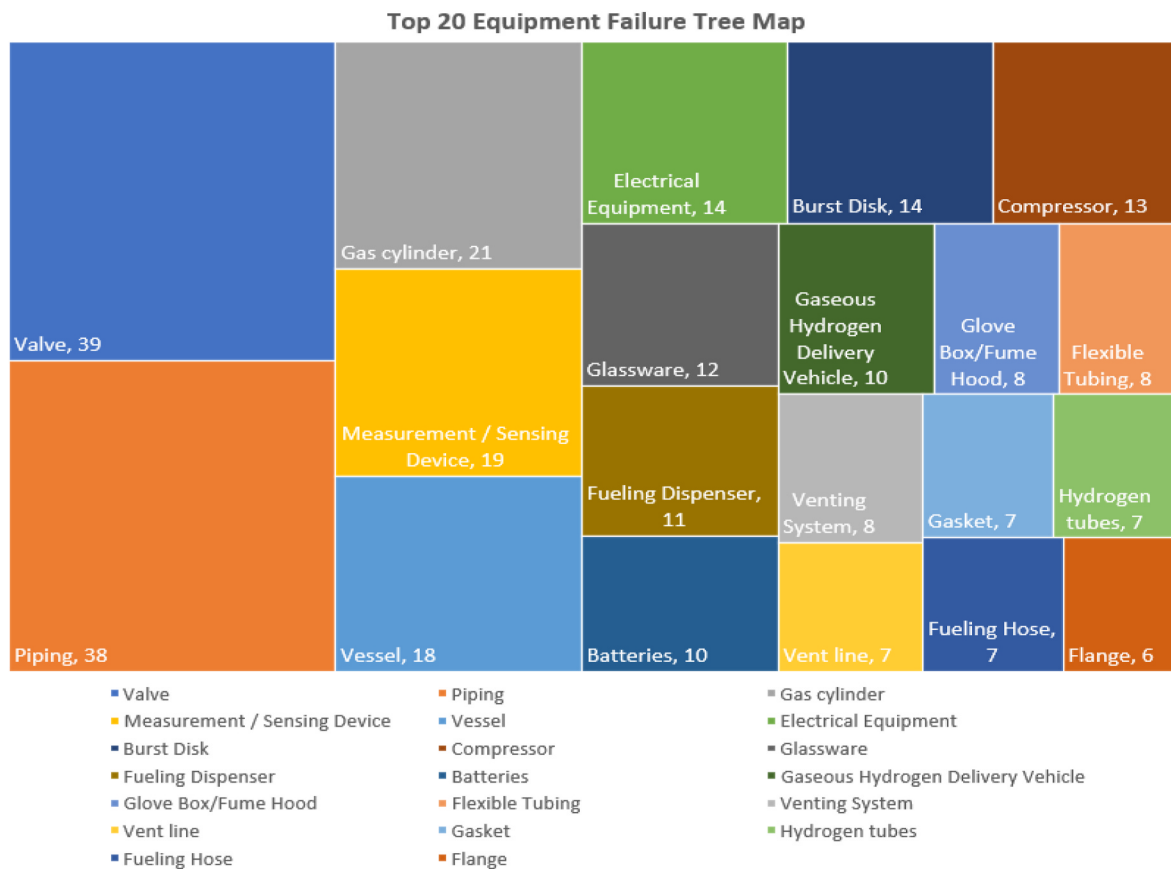
Hydrogen-related events were systematically coded into 438 contributing-factor elements and 416 equipment failure elements spanning multiple severity levels (Appendices A and B). Because individual incidents frequently involved multiple contributing factors and multiple equipment failures, each event was decomposed into contributing factor–failure pairs and treated as the analytical unit in the contingency analysis. This approach enabled examination of systemic relationships among causal elements rather than assuming mutual exclusivity at the incident level. A chi-square test of independence was applied to assess associations between nine contributing-factor categories and thirteen equipment-failure categories.

The results demonstrated a statistically significant association between contributing factors and equipment failures, $\chi^2(96, N = 289) = 120, p = 0.005$, Cramér's $V = 0.23$ (indicating a small-to-moderate effect size). While Cramér's V quantified the overall association strength (global effect), cell-level standardised residuals (r) were calculated to identify specific contributing factor–failure pairings that disproportionately drove the chi-square result. The strongest couplings were identified between monitoring and oversight deficiencies and safety equipment failures ($r = 7.47$), training and protocol gaps and laboratory equipment failures ($r = 4.14$), software and technical issues and sensing device malfunctions ($r = 3.88$), and procedural weaknesses and

Table 6

Summary of qualitative key elements, codes and themes of equipment failures associated with hydrogen occurrences, with frequency occurrence in brackets.

	Key Elements	Codes	Themes
Equipment Vulnerability	Gas cylinder, Hydrogen tubes, Hydrogen Storage Equipment, Dewar, Hydrogen Cryostat, Air-Tight Submersible Battery Case, Battery Storage Container, Atmospheric Storage Tank, Pulp Storage Tank, Sodium Hydride Container, Balloons	Hydrogen Storage Systems (151)	Storage Systems
	Waste Storage Drums, Radioactive Waste Storage Vessel, Acid leaching tanks, Refuse Incinerator, Emissions Treatment	Storage and Waste Management (42)	
	Liquid Hydrogen Delivery Vehicle, Gaseous Hydrogen Delivery Vehicle, Vehicle carrying hydrogen balloons, Vessels	Hydrogen Delivery Systems (40)	Delivery Systems
	Electrical Equipment, Batteries, Glove Box/Fume Hood, Main Generator Stator Cooling Water System, Pump, Environmental Chamber, Chemical Separations Unit	Support Systems and Accessories (40)	
	Water Electrolysis System, Hydrogen Production/Use Systems, Electrolyzers	Hydrogen Production Systems (39)	Production Systems
	Fuel Cell, Fuel Cell Vehicle	Energy Conversion Systems (26)	
	Compressor, Heat Exchanger, Process Vessels, Furnace, Reactor, High-Pressure Reactor Cell, Fixed-catalyst-bed tubular reactor, Industrial Heater, Chemical Separations Unit, Laboratory-scale oil bath, Oven, Heat Exchanger, Industrial Heater, Furnace	Processing and Reaction Equipment (18)	
	Microbiological Anaerobic Chamber, Laboratory-scale oil bath, Pool cells filled with water, Glass Lathe, Fixed-catalyst-bed tubular reactor, Refuse Incinerator, Chemical Separations Unit, Ball Mill, Balloons, Glassware	Lab and Research Equipment (16)	
	Piping, Flexible Tubing, Vent line, Fuelling Hose, Vent piping and cap, Vent Stack Cap, Burst Disk, Compressor, Fuelling Dispenser, Quick disconnect fittings, Flange, Pressure Transducer, Gas Chromatograph, Retort, Valve, Burst Disk, Gasket, Flange, Manual valve, Quick disconnect fittings, Manual valve, Hose	Hydrogen Fittings and Handling Equipment (16)	Flow Control Systems
	Bolts, Crafts Tools, Chisel, Pipe Wrench, Construction Tools, Non-sparking tools, Hydraulic Jacks, Angle Grinder	Tools and General Equipment (15)	
	Venting System, Exhaust Fan, Positive Pressure Fan, Exhaust Fan	Ventilation and Exhaust Systems (5)	
	Fire-Extinguishing Equipment, Electrical Safety Interlocks, Emergency shutdown procedures and disconnects, Inadequate Maintenance, Alarm Annunciator	Safety Equipment and Procedures (4)	Safety and Monitoring Systems
	Measurement/Sensing Device, IR spectrometer, Pressure Transducer	Measurement and Sensing Devices (4)	

**Fig. 4.** Tree map of 20 equipment failure elements, integrating 416 key elements, 13 codes and 5 themes among 222 hydrogen accident/incident occurrences.

hydrogen production system failures ($r = 3.17$). In contrast, most other contributing factor–failure combinations exhibited only small or negligible deviations from independence ($|r| < 2$), suggesting that operational risk concentrates in a limited number of high-impact pathways rather than being uniformly distributed across system components (Table 7) (see Table 8).

5. Discussion

The thematic analysis provides valuable insights into the multifaceted nature of risks in safety-related accident/incident investigations across industries [38,39]. By addressing technical reliability, organizational processes, individual performance, operational resilience, and external influences, aviation industries can significantly enhance risk management and safety outcomes. Through these lessons learned, to the prevalent contributing factors associated with system failures across hydrogen-related accidents/incidents, the hydrogen industry can foster a safer and more resilient environment, supporting the sustainable growth of hydrogen technologies in aviation and beyond [11]. Beyond the practical findings, this study also offers several methodological contributions. By combining expert-driven theme development with binary coding and chi-square analysis, the study bridges qualitative pattern recognition and quantitative association testing, demonstrating statistically supported links between socio-technical factors and specific system vulnerabilities. The use of heat maps and radar charts provides a transferable visual analytics toolkit for stakeholders who need to prioritise hazards, design safety indicators, and inform future hydrogen-powered aircraft concepts under Clean Sky-style programmes. Taken together, this mixed-methods approach surpasses previous hydrogen safety work, which has typically focused on descriptive statistics, and provides a replicable framework for leveraging lessons learned from hydrogen industries to support emerging aviation applications.

5.1. Lessons learned from contributing factors of hydrogen occurrences

A radar chart is a graphical tool to visually represent multivariate data, displaying multiple quantitative variables and their relationships on a pentagon plot. Each axis represents a variable, and the data points are connected to form a web-like shape [40]. This makes the comparison of relative contributing factors from hydrogen-related accident/incident occurrences simpler to visualise, across the five different themes (Table 5 & Fig. 5). There is a pattern of multiple-to-one phenomena; one occurrence may have involved multiple key elements from different categories [13,41]. Therefore, the total percentage of the five themes will be over 100%. The radar chart revealed that Individual Unsafe Acts had the highest incident occurrence rate (99), followed by Technical Failures (79), Organizational Processes (64), Operational Breakdown (48), and External Influences (10) as contributing factors. Although, the radar chart revealed that Technical Failures had the highest accident occurrence rate (26), followed by Individual Unsafe Acts (12), Organizational Processes (10), Operational Breakdown (6), and External Influences (3) as contributing factors.

By examining these themes we gain an understanding of the risks associated, enabling aviation industries to prioritise targeted interventions to mitigate the associated risks. For example, the significant presence of incidents in Individual Unsafe Acts did not reflect in the highest accident occurrences, seen in Technical Failures. Although, significant incident occurrence increases the risk of these individual themes of serious accidents to develop without targeted intervention. These can include, but not limited to: Audits, increased inspection and maintenance intervals of hydrogen equipment with associated risks, and proactive reporting culture with subsequent investigation and necessary action to rectify.

The theme of Individual Unsafe Acts accounts for 63.1% of the total **occurrences** and emerges as the most significant factor across all

severity levels, with 12 accidents, 99 incidents, 17 near misses, and 12 non-consequences. This theme highlights the pervasive role of human behaviour in safety outcomes, underscoring the necessity for comprehensive training programs, rigorous safety protocols, and a strong safety culture. Human factors emerge as the most significant contributors to hydrogen-related incidents. This category encompasses human errors, lapses in situational awareness, and poor decision-making. These individual unsafe acts underline the inherent vulnerability of human operators managing complex and high-stakes operations. The findings suggest that while many incidents remain minor, the potential for severe consequences cannot be ignored. Addressing these issues requires a strong emphasis on human factors engineering, comprehensive training programs, and cultivating a robust safety culture. Simulation-based training and real-time feedback mechanisms are critical to enhancing operator awareness and individual decision-making capabilities, while interventions like fatigue management and cognitive workload reduction can further minimize human errors in flight operations for future hydrogen-powered aircraft.

The theme of Technical Failures contributes to 56.3% of the **occurrences**, with a notable presence across all severity levels: 26 accidents, 79 incidents, 16 near misses, and 4 non-consequences. Equipment malfunctions, design flaws, and inadequate maintenance practices collectively underscore the safety concerns of technical integrity in hydrogen operations. While the contribution of technical issues spans from minor incidents to severe accidents, the analysis reveals that a significant proportion of these failures could be mitigated through robust engineering standards and proactive safety measures. Regular safety audits, predictive maintenance systems, and condition monitoring technologies are instrumental in addressing these risks. Furthermore, incorporating redundancies and fail-safes during the design phase can help ensure system resilience and reliability.

The theme of Organizational Process Issues comprises 42.3% of the total **occurrences**, including 10 accidents, 64 incidents, 13 near misses, and 7 non-consequences. This theme points to deficiencies in standard operating procedures, management oversight, and communication. The presence of these issues across all severity levels highlights the need for organizational improvements, including clearer procedures, stronger management practices, and better communication strategies. Such organizational process issues highlight a systemic challenge where gaps in leadership, documentation, or procedural clarity compromise safety. Aviation industries should focus on fostering a just culture that encourages reporting and addressing process deficiencies. Implementing regular process audits and engaging employees in safety discussions can help identify and rectify organizational process issues to implement innovative hydrogen-powered aircraft for commercial operations.

The theme of Operational Breakdowns represents 28.4% of incidents, with 6 accidents, 48 incidents, 7 near misses, and 2 non-consequences. This theme involves failures in operational practices, inadequate responses to deviations, and insufficient planning. The presence of operational breakdowns in both severe accidents and less severe incidents indicates the importance of maintaining operational discipline and quality control. Enhancing operational planning and monitoring technology, providing comprehensive training on emergency procedures, and developing contingency plans are essential steps to mitigate these risks. Aviation industries should consider adopting advanced process control technologies and decision support systems for front-line operators to enhance operational reliability. The findings align with previous research on developing prevention strategies that should be associated with human performance and organizational management in a risk assessment framework [29].

The theme of External Influences contributed to only 7.2% of the total incidents, including 3 accidents, 10 incidents, 1 near miss, and 2 non-consequences. This theme encompasses environmental conditions and external pressures that impact operations. Although less frequent, external influences can have significant effects when they occur, such as the Fukushima Daiichi Nuclear Power Station Disaster [42]. To mitigate

Table 7

Chi-square test of association between codes of contributing factors and equipment failures in hydrogen occurrences along with absolute standardized residual.

Contributing Factors	Equipment Failure	Hydrogen Fittings and Handling Equipment	Support Systems and Accessories	Processing and Reaction Equipment	Hydrogen Delivery Systems	Hydrogen Storage Systems	Measurement and Sensing Devices	Lab and Research Equipment	Tools and General Equipment	Ventilation and Exhaust Systems	Safety Equipment and Procedures	Energy Conversion Systems	Storage and Waste Management	Hydrogen Production Systems
Human Factors	χ	0.83	1.00	0.83	0.01	4.16	1.24	0.00	0.36	0.64	0.10	0.41	0.00	0.96
	p	0.36	0.32	0.36	0.94	0.04	0.27	0.95	0.55	0.42	0.75	0.52	0.96	0.33
	r	0.91	1.00	0.91	0.08	2.04	1.11	0.07	0.60	0.80	0.32	0.64	0.05	0.98
Procedures and Operations	χ	0.10	0.10	0.66	0.07	0.37	0.51	0.11	0.05	0.60	0.97	0.78	0.30	10.06
	p	0.75	0.75	0.42	0.79	0.54	0.48	0.74	0.83	0.44	0.32	0.38	0.58	0.00
	r	0.32	0.32	0.81	0.26	0.61	0.71	0.33	0.21	0.78	0.98	0.88	0.55	3.17
Equipment and Design	χ	1.39	0.68	0.01	0.46	3.42	0.44	2.43	0.69	1.84	0.00	0.75	0.56	0.56
	p	0.24	0.41	0.93	0.50	0.06	0.51	0.12	0.41	0.17	0.95	0.39	0.45	0.45
	r	1.18	0.83	0.09	0.68	1.85	0.66	1.56	0.83	1.36	0.07	0.86	0.75	0.75
Training and Protocols	χ	0.29	0.00	0.24	0.79	1.63	0.64	17.11	0.19	0.12	0.64	0.46	0.38	0.38
	p	0.59	0.96	0.63	0.37	0.20	0.43	0.00	0.67	0.73	0.42	0.50	0.54	0.54
	r	0.54	0.05	0.49	0.89	1.28	0.80	4.14	0.43	0.34	0.80	0.68	0.62	0.62
Inspection and Maintenance	χ	0.40	0.44	0.53	0.06	2.52	0.18	1.17	0.78	0.99	0.45	0.36	1.98	0.27
	p	0.53	0.51	0.47	0.81	0.11	0.67	0.28	0.38	0.32	0.50	0.55	0.16	0.60
	r	0.63	0.66	0.73	0.24	1.59	0.43	1.08	0.89	0.99	0.67	0.60	1.41	0.52
Environmental and External Factors	χ	0.96	0.07	0.10	1.48	0.21	0.02	0.67	0.23	0.57	2.11	0.21	0.16	0.16
	p	0.33	0.79	0.76	0.22	0.65	0.90	0.41	0.63	0.45	0.15	0.65	0.69	0.69
	r	0.98	0.26	0.31	1.22	0.45	0.13	0.82	0.48	0.76	1.45	0.46	0.39	0.39
Communication and Management	χ	0.99	0.78	0.08	0.70	0.68	0.84	0.31	0.29	0.27	0.12	8.42	0.07	0.07
	p	0.32	0.38	0.77	0.40	0.41	0.36	0.57	0.59	0.61	0.73	0.00	0.79	0.79
	r	0.99	0.88	0.29	0.84	0.82	0.92	0.56	0.54	0.52	0.35	2.90	0.27	0.27
Software and Technical Issues	χ	0.35	0.11	0.11	0.10	0.10	15.06	0.04	0.04	0.04	0.02	0.01	0.01	0.01
	p	0.55	0.74	0.74	0.75	0.76	0.00	0.83	0.84	0.85	0.90	0.91	0.92	0.92
	r	0.59	0.33	0.33	0.32	0.31	3.88	0.21	0.20	0.20	0.13	0.12	0.10	0.10
Monitoring and Oversight	χ	0.35	0.11	0.11	0.10	0.10	0.06	0.04	0.04	0.04	55.82	0.01	0.01	0.01
	p	0.55	0.74	0.74	0.75	0.76	0.81	0.83	0.84	0.85	0.00	0.91	0.92	0.92
	r	0.59	0.33	0.33	0.32	0.31	0.24	0.21	0.20	0.20	7.47	0.12	0.10	0.10

Table 8

Mapping of high-frequency hydrogen system failure themes to representative aircraft hydrogen system modules.

Thematic Failure Theme	Representative Aircraft Hydrogen System Module	Primary Aviation Relevance
Flow Control Systems (valves, piping)	LH ² feed lines, isolation valves, pressure regulation systems	Leak prevention, isolation, explosion risk control
Storage Systems	Cryogenic LH ² tanks, containment structures	Structural integrity, boil-off management
Delivery Systems	Ground-to-aircraft fuelling interfaces	Human-system interaction, hose rupture risk
Production/Processing Systems	Onboard fuel conditioning, heat exchange systems	Thermal control, material compatibility
Safety & Monitoring Systems	Hydrogen sensors, alarms, emergency shut-off	Early detection, fault tolerance

these risks, it is essential to conduct thorough risk assessments and implement adaptive strategies that enhance resilience to external factors. Aviation industries can benefit from developing robust emergency response plans that account for various external scenarios, such as extreme weather events or supply chain disruptions due to unexpected external influences.

5.2. Lessons learned from system failures of hydrogen occurrences

The thematic analysis classifies system failures associated with hydrogen occurrences into five primary categories; the highest incident occurrences are (1) **Flow Control systems (124)**, followed by (2) **Delivery Systems (65)**, (3) **Production Systems (34)**, (4) **Storage Systems (31)**, and (5) **Safety and Monitoring Systems (23)** (Table 6 and Fig. 6). These categories represent critical components and processes in hydrogen operations and provide insights into the underlying factors driving system failures [23]. These occurrences reveal significant trends and lessons learned from hydrogen industries which can be applied to aviation industries when developing innovative hydrogen-powered

aircraft for commercial operations. This substantial concentration in these categories indicates that there may be systemic issues impacting these critical components that warrant immediate and focused investigation to enhance the safety management system [43].

Flow Control Systems emerge as the most critical theme, with a total of 182 failures, accounting for 82.0% of occurrences, with a notable presence across all severity levels: 13 accidents, 124 incidents, 40 near misses, and 5 non-consequences. The analysis reveals that the valves and piping are the most frequent sources of failure: Valves with 39 occurrences (17.6%), and piping, with 38 occurrences (17.1%), together constitute nearly 35% of the total failures. This theme includes various components crucial for regulating and managing flow, such as valves, pumps, and regulators. The high frequency of failures in this category underscores its critical role in ensuring system stability and operational efficiency. Given the significant proportion of failures, it is essential to focus on enhancing the design, maintenance, and operational procedures related to the flow control equipment [44].

Delivery Systems follow with 82 (36.9%) failures, with a notable presence across all severity levels: 5 accidents, 65 incidents, 8 near misses, and 4 non-consequences. This category encompasses equipment responsible for the transportation and delivery of materials, such as hoses, delivery vehicles, and dispensers. These systems are vital for the safe and efficient distribution of hydrogen but are liable to technical failures, such as material degradation or pressure containment issues. Additionally, human factors issues during handling and operational lapses contribute to failures in this category. Addressing these challenges requires improved material selection, regular inspections, and better training for personnel involved in delivery operations [45].

Production Systems report 49 (22.1%) failures, with a notable presence across all severity levels: 8 accidents, 34 incidents, 5 near misses, and 2 non-consequences. This category includes equipment used in the production and processing stages, such as reactors and processing vessels. The notable number of failures highlights the importance of maintaining high standards in production systems to avoid disruptions and ensure consistent output. This research revealed that failures in this category are linked to technical issues, such as equipment wear or process inefficiencies, operational breakdowns due to inadequate

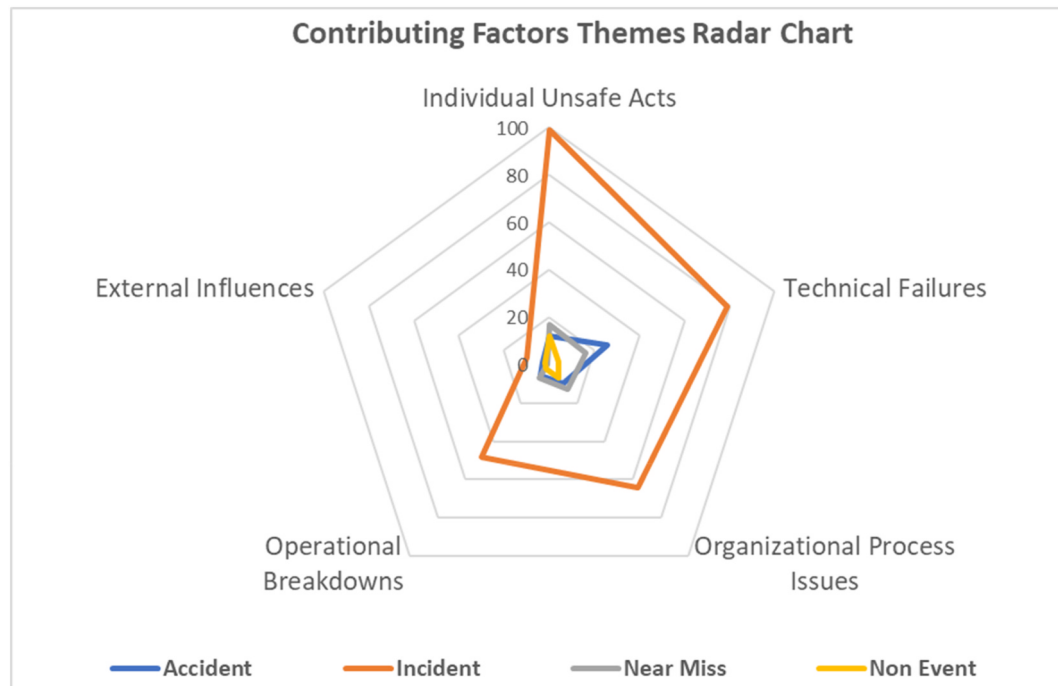


Fig. 5. Radar chart demonstrating five dimensions of contributing factors, with severity levels of hydrogen accident/incident occurrences based on theme analysis (one occurrence may have several contributing factors).

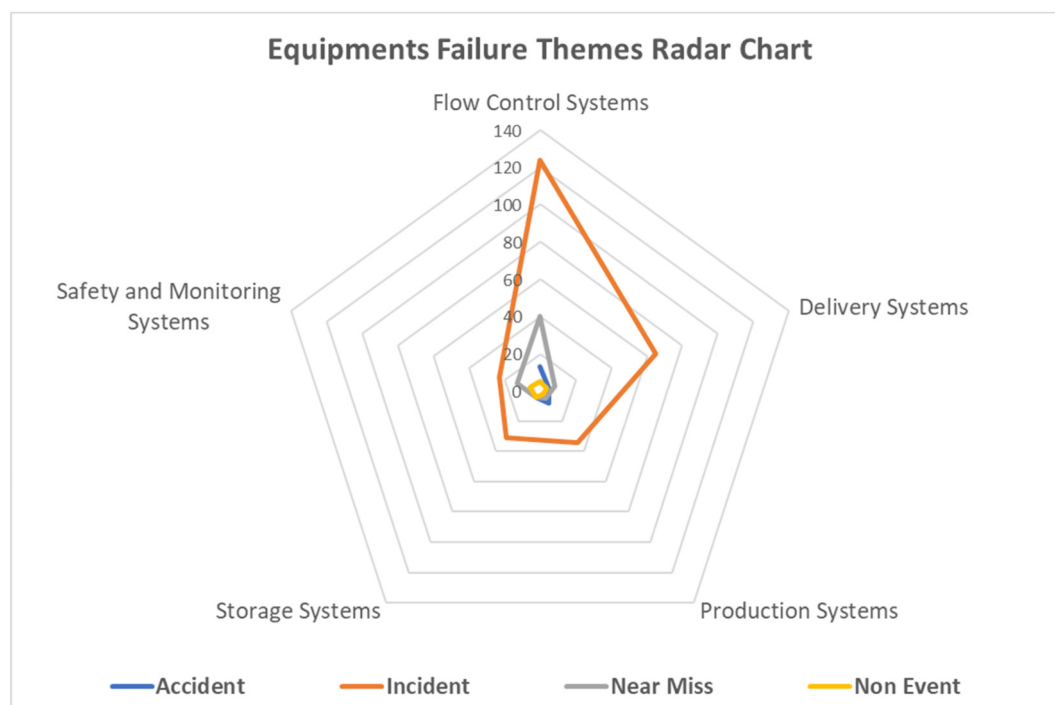


Fig. 6. The associations of system failures and hydrogen accident/incident occurrences with different severity levels based on theme analysis (one occurrence may have been involved in several system failures).

process control, and individual unsafe acts stemming from insufficient training [46].

Storage Systems account for 43 (19.4%) failures, with a notable presence across all severity levels: 4 accidents, 31 incidents, 4 near misses, and 4 non-consequences. This theme involves equipment related to storing materials, including tanks and storage vessels. The frequency of failures in this category emphasizes the need for rigorous risk management and regular inspections to prevent storage-related incidents. The storage systems are essential for hydrogen containment but are vulnerable to human errors during handling, inadequate maintenance, and operational shortcomings [47]. While technical failures are less frequent in this category, the impact of storage failures can be severe, leading to leaks, contamination and explosion. The findings of current research can enhance design standards, implement stringent monitoring protocols, and provide comprehensive training in aviation industries, which can reduce storage-related risks both in the airport and within the aircraft.

Safety and Monitoring Systems experience 42 (18.9%) failures, with a notable presence across all severity levels: 23 incidents, 13 near misses, and 6 non-consequences. This category includes equipment designed to monitor and ensure safety, such as sensors, alarms, and safety interlocks. Although these systems are designed to prevent or mitigate incidents, failures in this category are often due to technical faults or human lapses in using or maintaining these systems. Ensuring their effectiveness requires both technological upgrades to improve reliability and rigorous training to foster proper use and maintenance practices. The reliability and functionality of these systems are crucial to ensuring timely detection of issues and preventing accidents/incidents, thereby safeguarding both personnel and equipment.

5.3. Association between contributing factors and system failures impacted occurrences

The association between contributing factors and system failures in hydrogen-related occurrences is both intricate and pivotal for understanding the underlying causes of incidents and accidents. The chi-

square analysis highlights a statistically significant association ($p = 0.005$), revealing the interplay between contributing factors and system failures in occurrences. This association underscores how human, technical, and organizational elements interact with different hydrogen-related systems to drive safety outcomes, varying across incident severity levels, from non-consequential events to severe accidents. The chi-square test is a non-parametric test, meaning it does not assume any specific distribution for the data. This makes it suitable for the often uneven and non-normal distribution of incidents in safety-related datasets [48]. The chi-square test is suitable to accommodate these disparities in the datasets without requiring data transformation [49]. Severe accidents are often linked to combinations of human errors, technical failures, and organizational deficiencies, highlighting the compounding nature of these interactions. Furthermore, the combination of Human Error in the contributing Factors and Flow Control System in the System Failures themes is the most hazardous scenario, which is the highest risk associated with severe accidents (Figs. 5 and 6).

The high occurrences of equipment failures suggest potential issues with the design, installation, and maintenance of these components. Problems in these areas could lead to leaks or blockages, increasing the risk of hydrogen escape and subsequent ignition [50]. Addressing these 86 unique vulnerabilities of equipment requires rigorous quality assurance on both the maintenance of materials and precise inspection protocols to identify early signs of wear and tear, and design flaws. However, we must be aware that a key limitation of TA is that the frequency appearing in incident reports does not necessarily correspond to the underlying risk or severity. Frequencies may be influenced by reporting practices, investigation scope, and the visibility of certain types of failures; therefore, they cannot be taken as a wide-ranging measure of severity. Thematic analysis of reports is most appropriately viewed as a way to surface recurring patterns and candidate areas for further quantitative analysis and qualitative consideration, rather than as a stand-alone method for ranking risks. Human error emerges as a significant factor in failures across control flow, storage and delivery systems [50,51]. These errors often stem from inadequate training, improper adherence to protocols, or fatigue, underscoring the urgent

need for enhanced training programs and rigorous procedural compliance to mitigate such risks. Valves and piping failures in the theme of Flow Control Systems frequently involve improper handling or errors in operational procedures, such as failure to follow maintenance protocols or misjudgements during valve operation. These interactions lead to leaks, pressure containment failures, or hydrogen releases; the failures of hoses and delivery vehicles in the theme of Delivery Systems are associated with Unsafe Acts of Operators during hydrogen transport. These include improper loading or disconnect procedures, which are associated with system breakdowns like hose ruptures or vehicle malfunctions. Training gaps and a lack of situational awareness are common root causes.

The Space Shuttle *Challenger* disaster (1986) illustrates how hydrogen-related hazards can emerge from socio-technical interactions rather than solely from technical failures. The accident culminated in the structural failure of the External Tank and the rapid release and combustion of cryogenic propellants, containing liquid hydrogen. The initiating event was the degradation of the solid rocket booster O-rings in unusually cold ambient conditions, demonstrating how environmental variability can reduce component sealing performance and enable tightly coupled failure propagation. However, the loss of *Challenger* cannot be explained solely by software and hardware components. It also reflected organisational and operational influences, including the failure to convert engineers' concerns about low-temperature performance into conservative launch, decision-making shaped by authority gradients, and the normalisation of deviance after repeated seal erosion was observed without immediate catastrophic outcomes. The accident was attributed to many failures that were mishandled due to a lack of sufficient risk assessment capability by individuals involved in the decision-making process for the launch. Effective RMS can help to capture early indicators to failure in organisations, and can provide a rationale for safe continuation in operations, which was missing in this accident [41,52]. For LH₂ applications in aviation and aerospace, this case highlights that safe adoption requires more than robust cryogenic system design. It depends on aligning leak detection, annunciation, and fault-management logic with clear operational limits, transparent risk communication, and decision-making criteria, especially when operations approach or exceed validated envelopes.

While the source occurrences span multiple industrial contexts, the mapped failure themes directly correspond to hydrogen aircraft system modules subject to similar physical hazards, including cryogenic temperatures, high-pressure flow control, leakage sensitivity, and ignition risk. Applicability to aviation is bounded by additional constraints such as redundancy requirements, vibration loading, certification safety margins, and extreme thermal gradients. Nevertheless, the recurrence of flow-control and containment failures across sectors highlights transferable vulnerability mechanisms relevant to aircraft LH₂ architectures, particularly during fuelling operations, transient pressure states, and emergency venting scenarios.

The thematic codebook may be operationalised within standard aviation safety methods such as Functional Hazard Assessment (FHA) and Failure Modes and Effects Analysis (FMEA). For example, recurrent flow-control failures identified in the dataset (valves and piping leaks) can be translated into FHA hazard conditions such as “uncommanded hydrogen release during feed-line operation,” with severity assessed against fire and explosion outcomes. In FMEA, specific failure modes including valve seal degradation or vent blockage can be evaluated for likelihood, detectability, and mitigation through redundancy and sensor placement. Similarly, storage-system vulnerabilities can inform containment breach scenarios under cryogenic stress conditions.

6. Conclusion

Hydrogen's potential as a sustainable aviation fuel forms a critical part of the ICAO vision for achieving net-zero emissions by 2050, and the ICAO Sustainable Aviation Fuels guidance highlights its key role in

decarbonising the sector. This study contributes to that agenda by applying thematic analysis to 222 hydrogen-related occurrences, revealing the multifaceted nature of risk across human operators, technical, organisational, and environmental dimensions. The prevalence of individual unsafe acts alongside technical failures indicates that human and technical factors are closely intertwined and must be managed together, rather than in isolation. Our findings suggest several practical and actionable strategies for developing future hydrogen-powered aircraft, drawing on lessons learned. First, the recurrent patterns of individual actions, communication issues, and procedural deviations support the need for targeted training that emphasizes hydrogen-specific hazards, leak recognition, emergency response, and strict adherence to isolation and purging procedures. Second, the frequency of equipment-level failures underlines the importance of design-for-safety principles, robust component selection, and predictive maintenance regimes focused on valves, piping, sensors, and containment barriers identified in the thematic analysis. Third, the use of radar charts and other visual analytics provides a practical tool for operators, manufacturers and regulators to identify “hot spots” in the risk landscape to allocate the resources in future operations.

At a systems level, the significant associations between contributing factors and system failures highlight the need for an integrated safety management approach that combines human factors, innovative technologies, operational discipline, and resilience to external influences. This includes embedding hydrogen-specific lessons into safety management systems, auditing practices, and concept-of-operations development for hydrogen-powered aircraft. This study has several limitations. The analysis is based on secondary incident reports drawn from diverse hydrogen applications rather than current aviation operations. The reporting practices, investigation scope, and data completeness may influence which factors are documented. Thematic frequencies indicate the prevalence of reported issues in the dataset but do not directly measure underlying risk related to severity. In addition, transferring lessons from industrial and ground-based hydrogen systems to future aircraft architectures requires careful engineering judgement and further validation. Future research should therefore focus on integrating the hydrogen-specific codebook and patterns identified here into quantitative risk models for hydrogen-powered aircraft. It will be necessary to incorporate explicit severity weighting, and explore how human-machine interface design and operational concepts can be adapted in simulators and testbeds. By doing so, insights from existing hydrogen safety sectors can more effectively support the safe and sustainable development of hydrogen technologies for the Clean Sky in the rapidly evolving aviation sector.

CRedit authorship contribution statement

Wen-Chin Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization. **Hamed Amanzadeh:** Writing – original draft, Methodology, Formal analysis. **James Blundell:** Writing – review & editing, Visualization, Methodology. **Declan Saunders:** Writing – review & editing, Visualization. **Pete Beecroft:** Writing – review & editing, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2026.155027>.

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