International Journal of Hydrogen Energy 183 (2025) 151155

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Differentiating hydrogen-driven hazards from conventional failure modes in hydrogen infrastructure

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ARTICLE INFO

Keywords:
Hydrogen
Safety
Failure mechanisms
Pipeline

ABSTRACT

Hydrogen is a promising carbon-free energy carrier for large-scale applications, yet its adoption faces unique safety challenges. Microscopic physicochemical properties, such as high diffusivity, low ignition energy, and distinct chemical pathways, alter the safety of hydrogen systems. Analyzing the HIAD 2.0 incident database, an occurrence-based review of past hydrogen incidents shows that 59% arise from general industrial failures common to other hydrocarbon carrier systems. Of the remaining 41%, only 15% are unequivocally linked to the fuel's unique properties. This study systematically isolates hazards driven by hydrogen's intrinsic properties by filtering out confounding factors, and provides an original clear characterization of the different failure mechanisms of hydrogen systems. These hydrogen-specific cases are often poorly described, limiting their contribution to safety strategies and regulations improvement. A case study on pipeline failures illustrates how distinguishing hydrogen-specific hazards supports targeted risk mitigation. The findings highlight the need for evidence-based regulation over broadly precautionary approaches.

1. Introduction

As an energy carrier, hydrogen poses significant safety challenges, primarily due to its high destructive potential during uncontrolled combustion. Compared to other commonly used gaseous fuels, hydrogen exhibits a range of unique physicochemical properties, including a broad flammable range in air (4%–75%) [1], a high laminar burning velocity (2.8 m/s) [2], and a low minimum ignition energy (0.02 mJ) [3]. These characteristics not only make hydrogen more prone to forming flammable mixtures upon leakage, but also allow flames to propagate rapidly and produce elevated combustion pressure peaks once ignition occurs. As a result, hydrogen exhibits a much higher destructive potential under accident conditions than conventional fuels such as natural gas or propane. In addition, the small molecular size of hydrogen, with a Van der Waals radius of 110 pm that facilitates its diffusion in solids [4], makes it more prone to leakage and introduces specific degradation mechanisms in materials. These characteristics result in distinct behaviors throughout the entire accident evolution process, including leakage, dispersion, ignition, and combustion. More importantly, when these properties interact, they further increase the system's unpredictability. For example, hydrogen's small molecular size requires high-pressure storage and delivery to maintain energy efficiency. However, higher pressures can significantly alter its leakage and dispersion patterns as well as ignition and combustion behavior. This inevitably high-risk nature demands that safety strategies be grounded in the specific behavioral mechanisms of hydrogen rather than adapted directly from the safety practices developed for other energy carriers. Understanding and controlling hydrogen's behavior under uncontrolled conditions is therefore a critical prerequisite for its safe and widespread application.

The hazards associated with hydrogen's unique properties have long been recognized, and the field of hydrogen safety has attracted substantial research efforts. Fundamental understanding has been developed across key stages of accidental scenarios, including leakage, dispersion, ignition, and combustion. The leakage process has been systematically classified into subsonic jets, choked jets, and underexpanded jets, while dispersion behaviors are commonly distinguished between open and confined spaces [5]. Various ignition mechanisms have been proposed, such as reverse Joule–Thomson effect [6], electrostatic discharge-induced ignition [7–9], and diffusion ignition [10–12], yet no unified consensus has been reached, and many mechanisms remain difficult to reproduce under open environments or complex piping systems. In particular, experimental data on the minimum ignition energy (MIE) under extreme conditions (e.g., high pressure, low temperature) remain limited, posing significant challenges for the reliability of predictive models [13–16]. For the jet flame phase,

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https://doi.org/10.1016/j.ijhydene.2025.151155
Received 20 May 2025; Received in revised form 20 August 2025; Accepted 22 August 2025
Available online 7 October 2025

previous studies have established the relationship between jet morphology and flame structure, and identified transition boundaries between momentum- and buoyancy-dominated regimes based on the Froude number. For example, a Froude number greater than 1000 typically indicates momentum dominance, while a value below 10 indicates that buoyancy dominates the flame structure [17,18]. However, flame propagation and thermal radiation under more realistic application conditions, including confined geometries, obstruction-induced flow disturbances, and wall impingement, remain poorly understood [19]. Studies on flame acceleration (FA) and deflagration-to-detonation transition (DDT) have revealed key mechanisms, such as turbulence-enhanced combustion, pressure wave interactions, and flame instabilities [20–23]. Nonetheless, reliable criteria to predict whether DDT will occur under specific boundary conditions are still lacking. This limitation is especially critical in complex geometries, non-uniform mixtures, or irregular obstacle layouts, where existing experiments and simulations have limited generalizability [24,25]. Detonation, as the most extreme form of combustion, has been studied under idealized conditions, with notable progress in understanding detonation wave structure, the evolution of precursor shocks, and kernel formation mechanisms [20,26]. Yet, in real-world systems, such as high-pressure hydrogen pipelines or fuel cell vehicles, experimental validation is still lacking. Furthermore, numerical simulations are constrained by limitations in mesh resolution and chemical kinetics models [27]. Overall, while the theoretical research in hydrogen safety has established a strong foundation in fundamental physical processes, its reliable application to complex, real-world systems remains limited. This challenge becomes particularly significant in scenarios involving high-pressure rapid release, irregular structural configurations, or dynamic boundary conditions. Under such conditions, existing models often fail to predict accident evolution accurately, representing a critical bottleneck in the safe deployment of hydrogen technologies at scale.

The growing demand for improved safety strategies is primarily driven by the evolving role of hydrogen, which has shifted from an industrial feedstock to a clean energy carrier [28]. In particular, advances in water electrolysis technologies have enabled the production of hydrogen using renewable energy sources, thereby reinforcing its central position in global decarbonization efforts in line with the Paris Agreement and national carbon neutrality commitments [29]. As hydrogen applications extend beyond traditional industrial settings into more complex and widespread energy systems, the likelihood of exposure to variable environmental conditions increases significantly, and this leads to a corresponding escalation in potential safety risks [30,31]. This escalation can be characterized by three key trends. First, there is a shift from closed industrial facilities to open environments. Hydrogen is increasingly being used in urban transportation, residential energy supply, port operations, and mobile applications. These scenarios involve more diverse populations, varying safety levels, and typically lack the centralized control frameworks found in chemical plants [32]. For example, hydrogen refueling stations and residential hydrogen boilers have already been deployed in several countries, which has greatly expanded the range of potential exposure [33]. Second, the sector is transitioning from standardized processes to diverse technological pathways. While hydrogen production and storage were once dominated by uniform technologies such as steam methane reforming (SMR), today's approaches include high-pressure storage, cryogenic liquid hydrogen, metal hydrides, liquid organic hydrogen carriers (LOHCs), and hydrogen blending (H_2 & Nature Gas). These technologies differ significantly in terms of temperature, pressure, and material compatibility [34,35]. Third, hydrogen systems are evolving from static operation to dynamic and transient processes. Examples include the integration of wind-powered electrolysis with grid balancing, on-site hydrogen generation with mobile dispensing, and pressure cycling or flow fluctuations in transmission pipelines. These dynamic operating conditions create frequent system changes, induce transient stresses, and complicate the prediction of accident development [36,37]. A further transformation that should not be overlooked is the shift from single-material systems to complex multi-material architectures. Next-generation hydrogen systems commonly incorporate composite pressure vessels, polymer electrolyte membranes, ceramic components, and porous storage materials. However, existing design standards and lifetime assessment models are mainly developed for conventional metallic materials, which results in fundamental gaps in current safety evaluations [32,36]. These indicate that the core challenge does not stem from hydrogen's changing role as an energy vector. Rather, it lies in the absence of adequate data and analytical methods to support safe design practices and to manage unexpected failures in evolving real-world applications.

In practice, regulatory frameworks serve as the foundation for the safe use of hydrogen. Although several jurisdictions have issued specific codes, standards, and guidelines for emerging hydrogen applications, the overall regulatory landscape still faces three major challenges. The first challenge is the lack of global harmonization, which has resulted in a fragmented safety architecture. Divergent standards across regions increase the complexity of international cooperation and trade [38,39]. In contrast, the oil and gas sector achieved global standardization as early as the 1970s, largely driven by multinational companies such as Shell, working through organizations like IOGP, API, and ISO [40,41]. The hydrogen sector has yet to reach a comparable level of coordination. This is due to several factors: the industry is still in its early stages and lacks dominant global players; many key technologies such as fuel cells, high-pressure storage, and hydrogen blending are rapidly evolving, making it difficult to establish stable technical norms; and although institutions like ISO/TC 197 and the Hydrogen Council have been established. They have limited influence in setting and enforcing international standards compared to ISO/TC 67 or API. Moreover, unlike the oil sector, which experienced transformative regulatory reforms following catastrophic events like the Piper Alpha (1988) and Deepwater Horizon (2010) disasters, hydrogen as an energy carrier has not yet faced a comparable external crisis to drive alignment [42,43]. As a result, hydrogen-related safety regulations remain highly regionalized. For example, national standards on hydrogen blending differ significantly in blending ratios, material compatibility, and fire prevention requirements, hindering cross-border projects and global supply chain integration [44]. The second challenge is that the development of hydrogen standards consistently lags behind technological innovation. Revisions are often reactive, relying on lessons learned from past incidents or driven by major industry players and regulators. In rapidly evolving technology domains, this passive mechanism frequently fails to meet practical needs. A notable example is the application of LOHCs, where benzyl toluene has been used as a hydrogen storage medium since 2013. Despite its growing adoption in countries like Germany, Finland, the Netherlands, and Japan, no ISO, IEC, or NFPA standard currently exists to regulate the design, operation, or safety management of LOHC systems [45,46]. Most projects in this area rely on general hazardous goods transport regulations (e.g., UN 3082), lacking systematic technical guidance [47]. Even in relatively mature areas, such as high-pressure storage for hydrogen fuel cell vehicles, this delay is evident. Although 70 MPa onboard storage systems entered commercial use around 2010, the corresponding international fueling protocol (SAE J2601) was not officially released until 2014 [48], and major updates to accommodate heavy-duty vehicles and high-flow fueling only arrived in 2020 [49]. These examples illustrate a persistent pattern: technology deployment tends to precede standardization, leaving regulators to respond retrospectively, which creates structural misalignment between engineering progress and regulatory preparedness. The third challenge is the insufficient scientific basis for many current hydrogen safety guidelines, leading to either overly conservative rules that increase costs or overly permissive rules that fail to address real risks. For instance, the European Industrial Gases Association (EIGA) mandates a fixed 8-meter safety distance for liquid hydrogen storage, regardless of storage volume [39]. While this "one-size-fits-all" approach may be useful as a default baseline [Safety distances: Definition and values], it is poorly suited to diverse engineering contexts. What is needed instead are performance-based, scenario-specific safety criteria that account for variables such as storage capacity, potential leak volume, ventilation conditions, and proximity to occupied areas. Dynamic adjustments based on these factors, such as using probabilistic "risk-based spacing" rather than fixed physical separation, are widely adopted in high-risk sectors like petroleum refining [50]. Yet, the hydrogen industry remains in the early stages of transitioning from prescriptive, parameter-based standards toward risk-informed frameworks. Moreover, such methods require foundational data inputs, which remain limited. For example, two-phase behavior, condensation, freezing, and jet characteristics following cryogenic hydrogen leaks are still subject to large predictive uncertainties [51,52]. Collectively, this fragmented regulatory structure, coupled with the global drive for hydrogen innovation and a lack of risk-informed scientific assessment, makes current oversight highly susceptible to reactive, non-evidence-based decision-making. These reactions can, in some cases, hinder rather than enable technological progress. A well-known case from the sustainable energy sector is the International Civil Aviation Organization's (ICAO) temporary two-year ban on lithium battery transport in passenger aircraft in 2016. Although intended to reduce fire risk through better packaging, all previous incidents involving battery fires were unrelated to packaging deficiencies [53]. A similar reaction occurred in the hydrogen sector following the 2019 explosion at a hydrogen refueling station in Sandvika, Norway, which led to the temporary shutdown or suspension of refueling stations in Germany, Denmark, and South Korea [54]. The investigation later revealed that the incident was caused by a faulty burst disk in a high-pressure storage tank, not a systemic flaw in hydrogen technology. Nevertheless, the event significantly undermined public and investor confidence in hydrogen-powered transportation, delivering a serious setback to its deployment.

These challenges underscore the distinct and often compounding risks associated with hydrogen's intrinsic properties, particularly under complex real-world conditions where theoretical insights remain difficult to apply. As hydrogen technologies rapidly expand into more open, diverse, and dynamic applications, the limitations of existing regulatory frameworks become increasingly evident. These limitations include fragmented standards, slow update cycles, and insufficient scientific foundations, which often lead to unbalanced or reactive oversight. At the heart of these challenges is a fundamental limitation. The current safety management system lacks a systematic approach to distinguish between hazards that are inherently driven by hydrogen's unique physicochemical behavior and those that result from general engineering or operational issues. In addition, even when hydrogen-specific mechanisms are clearly involved, it often remains uncertain which intrinsic properties are the actual sources of risk. This dual ambiguity complicates both the classification of incidents and the development of targeted safety strategies, potentially leading to either an overgeneralization or a misinterpretation of hydrogen-related risks. To address this gap, this study proposes a mechanism-based analytical approach that classifies incidents according to whether they reflect behavior uniquely attributable to hydrogen. Rather than attempting to reconstruct every detail of complex accident scenarios, the approach focuses on identifying the presence and role of hydrogen-driven mechanisms. By applying this criterion to past incidents, this study aim to establish a clear framework for identifying hydrogen-specific hazards. This framework can serve as a foundation for more scientifically grounded and adaptable safety strategies that align with the evolving complexity of hydrogen deployment.

2. Past incidents: Discrimination of hydrogen-specific incidents

To identify which incidents reported in the hydrogen industry are caused by the unique properties of this gas, it is essential to pick a suitable incident database. Most incident databases are not specifically tailored to capture hydrogen-related events, yet many include incidents that are directly relevant to the hydrogen industry. The most notable are the Accident Risk Information System (ARIA), the Major Accident Reporting System (eMARS), the Failure and Accidents Technical Data System (FACTS), H2TOOLS, and the Hydrogen Incidents and Accidents Database 2.0 (HIAD 2.0) [55–58]. While ARIA, eMARS, and FACTS contain records of hydrogen-related incidents, they each have limitations. ARIA provides 395 incident records from 1974 to 2022, but it focuses on qualitative information and lacks the quantitative data to inform an in-depth analysis. In addition, the broad scope of ARIA means that the reports lack specificity when describing hydrogen-related events. eMARS focuses on major chemical accidents and offers high-quality data but includes only 96 hydrogen-related incidents between 1920 and 2022. This limited subset of incidents does not reflect the state of the industry and can create a bias in the outcome. FACTS on the other hand contains 481 hydrogen incidents and provides quantitative analyses. However, the database focuses more on the consequences of each accident than on the causes and the relation to hydrogen-specific properties. In contrast, H2TOOLS and HIAD 2.0 are databases specifically tailored to the hydrogen industry. H2TOOLS provides safety guidelines, incident reports, and risk assessment tools, offering practical solutions for hydrogen safety management. Unfortunately, the 221 hydrogen incidents reported do not feature structured quantitative data which limit its utility in the present case. HIAD 2.0 stands out as the most suitable database for the current analysis, with 752 recorded incidents from 1960 to 2023 and ongoing updates. The incidents recorded cover those of the other databases over that period. HIAD 2.0 offers a comprehensive focus on hydrogen-related incidents, and reports identified modes of hydrogen-specific failures. This database provides detailed categorization and in-depth causes comments, allowing discrimination between hydrogen-specific and general industrial accidents. This level of detail is required for optimizing safety strategies and regulations in hydrogen technologies, providing the targeted data necessary to enhance both understanding and prevention of hydrogen specific incidents.

2.1. HIAD 2.0 hydrogen incident database

HIAD 2.0 database sources global data from a variety of publicly available primary sources. It provides traceable links to each source, combining results from scientific articles, newspapers, industrial reports, and regional databases covering Europe (ARIA, eMARS, IChemE), Japan (RISCAD), and America (CSB, NTSB ,OHSA) [55,58]. This diversity of sources facilitates a comprehensive analysis of global hydrogen-related safety issues.

Each event in HIAD 2.0 features a description of the facilities, the consequences, the lessons learned, the nature of the events, and includes references. The information comes with a Quality Label indicating the level of report detail. The quality labels range from 2, describing an incident where most quantitative descriptors are missing, to 5, where lessons learned and root cause analyses are available with comprehensive technical details. Higher ratings facilitate more accurate identification and about half of the recorded incidents achieve a quality rating of 3 or higher. It is essential that accidents used for assessment have at least a quality label of 3 to ensure a sufficient description of the causes is available. The database provides insights into the causes of each incident, labeling them as Technical or mechanical causes, Operational causes, Organizational causes, Human errors, and Environmental or external causes. Though additional research is needed, this first classification supports a systematic identification of events that could have happened in similar facilities dedicated to a different energy carrier.

Given the rapid development of hydrogen applications in recent years [59] and the associated evolution of materials and technologies, the analysis focuses on accidents occurring between 2000 and 2024. This period, yields a total of 295 accidents with a Quality Label above 3 that can be systematically analyzed. The original dataset used for this classification is provided in the supplemental material and serves as the reference for the analysis.

Table 1
Comparison of properties of molecular hydrogen and propane in air. The heat of reaction is given per mol of oxygen consumed. The large discrepancy in density, diffusivity, MIE, and pressure of molecular hydrogen and propane stand out as key properties with implications for systems safety.

Property	Hydrogen H_2	Propane C_3H_8
Density (kg.m^{-3})	0.0899	2.0098
Diffusivity (cm^2 s^{-1})	0.76	0.1
Heat of reaction (kJ)	572	409
MIE (mJ)	0.02	0.25
Flammability range	4%–75%	2.2%–9.6%
Max. pressure (bar)	700	12

2.2. Classification of the incidents

The objective of this analysis is to single out hydrogen-specific incidents, focusing on hydrogen-specific properties and the root causes of accidents. Incidents are deemed "Hydrogen-specific" if, by nature, they could not have occurred in other energy carriers plants. To that end, the comparison is made with the following common carriers: natural gas, propane, ethylene, and gasoline vapor. The difference will be related to the unique properties of molecular hydrogen.

Molecular hydrogen stands out from other energy carriers due to its low molecular weight (2.02 g/mol), small molecular size (hydrogen has an atomic radius of 0.53 Å and a H–H bond length of 0.72 Å), and high H–H bond energy (436 kJ/mol). These microscopic properties have far-reaching consequences. Molecular hydrogen is a gas at standard temperature and pressure conditions (STP) characterized by a low density of 0.0899 kg.m^{-3}, a high diffusivity of 0.76 cm^2 s^{-1}, and high exothermic heat of reaction with oxygen of 572 kJ per mole of oxygen consumed [60,61]. Additionally, hydrogen exhibits a low minimum ignition energy (MIE) in air around 0.02 mJ and a wide flammability range in air between 4% and 75% by volume which set it apart from other energy carriers. And because of the low density, hydrogen systems usually feature exceptionally large pressures up to 700 bar to deliver a reasonable flow of energy. In contrast, propane's density is 2.0098 kg.m^{-3} and its diffusivity in air is 0.1 cm^2 s^{-1} at STP. Propane's exothermic heat of reaction is 409 kJ per mol of oxygen consumed, and the MIE in air is around 0.25 mJ for a flammability range between 2.2% and 9.6%. Propane is usually transported at pressures below 12 bar, which is much easier to handle than the pressure levels of hydrogen. The properties are summarized in Table 1 for at-a-glance comparison.

Inherently, these unique properties do not create hazards, but they can lead to situations which have not been addressed yet by the safety standards of the energy sector. Yet, it is expected that part of the accidents occurring in the hydrogen industry can also be found in other high-energy facilities since the sector as a whole is far from achieving 100% safety. The review of past incidents then helps narrow down problematic situations caused by hydrogen-specific properties and ultimately define hydrogen-specific hazards and mitigation measures. Incidents that lack sufficient information to determine the precise cause of a fire or explosion at a hydrogen facility can inform what areas of research need to be pursued. For instance, hydrogen has a such a low minimum ignition energy that it is often difficult to determine the exact cause of an ignition and assess whether other flammable gases would have ignited in the same situation.

Eventually, incidents in the HIAD 2.0 database are classified as "hydrogen-specific" if the root cause of the problem can be directly related to the unique properties of molecular hydrogen, "non hydrogen-specific" if a similar incident could have happened with a different energy carrier, and "unknown" if the there is not enough information available to discriminate between the two aforementioned cases. It is worth reiterating that this analysis does not consider the role of hydrogen on the impact of an incident, but rather focuses on the causes and the possibility of the incident to occur. Fig. 1 shows the relative distribution of each category and provides a breakdown of the leading causes. From this figure, "non-hydrogen-specific" incidents dominate the dataset, accounting for approximately 59%. Most incidents are indeed caused by issues such as human error, design flaws, and component malfunctions, which are not exclusive to hydrogen but apply to all energy carriers. On the other hand, "hydrogen-specific" incidents represent 15% of the total, where the unique physicochemical properties of hydrogen, such as its ability to cause material failure, play a significant role. Additionally, the "unknown" category accounts for 26%, highlighting gaps in data collection and incident reporting that make it difficult to accurately determine root causes. The fact that approximately a third of the causes cannot be clearly discriminated stresses the need to improve data collection and incident reporting practices for hydrogen-related incidents.

In the following section, representative cases will be analyzed to explore the sub-classifications represented in the outer circle of the chart in Fig. 1.

2.3. Non-hydrogen-specific hazards

Within the dataset, 59% of the incidents are classified as non-hydrogen-specific. This classification indicates that these incidents were not directly linked to the unique properties of hydrogen. Instead, their causes stemmed from factors commonly associated with other energy carriers or industrial systems.

The non-hydrogen-specific incidents can be categorized into six primary factors, as detailed in Fig. 1. The most significant factor is human error, accounting for 16% of the incidents. Human errors arise from operational mistakes, such as violations of safety procedures or misjudgments during critical tasks. For example, in Incident ID: 1024, an operator replaced a defective flange rods with one that had incompatible operating characteristics. This incompatibility led to material failure, resulting in a hydrogen leak and subsequent fire. Following closely, design issues are responsible for 15% of the incidents. These issues stemmed from flaws in equipment or system design that failed to adequately account for operational demands or safety requirements. In Incident ID: 938, the absence of preventive and mitigating measures tailored to the specific chemical process led to the production of a flammable mixture, which ultimately triggered an explosion.

Failures in equipment components (unrelated to hydrogen), categorized as component malfunctions, contribute to 13% of the incidents. These failures were often linked to factors such as aging, material fatigue, poor component quality, or insufficient maintenance. For instance, in Incident ID: 785, a low-level sensor in a cyclododecatriene system failed to detect critically low liquid levels. This failure allowed hydrogen to enter the production line, leading to a leak and subsequent fire. Driving incidents, which accounted for 12% of the non-hydrogen-specific incidents, were associated with transportation-related errors or collisions. For example, in Incident ID: 1089, a highway accident involving multiple vehicles and a trailer carrying high-pressure hydrogen cylinders caused damage to the cylinders. This damage resulted in hydrogen being released through a valve and a crack in the side of the cylinder, leading to ignition and combustion.

A smaller portion of incidents, 3%, were attributed to external interference and electrical issues. External interference incidents were caused by environmental or human factors, such as construction activities which are not included in the system or natural disasters. In Incident ID: 759, gradual soil settlement around an underground pipeline caused bending at a fixed structure. This exerted stress on the cathodic protection coupling, eventually leading to a hydrogen leak. Electrical issues, on the other hand, were linked to failures in electrical systems, such as power outages or equipment malfunctions. For instance, in Incident ID: 1075, a lightning strike caused a sudden voltage drop at a chlor-alkali plant using the mercury process. The inadequate power recovery system failed to account for improper component responses to the voltage drop, leading to the accumulation

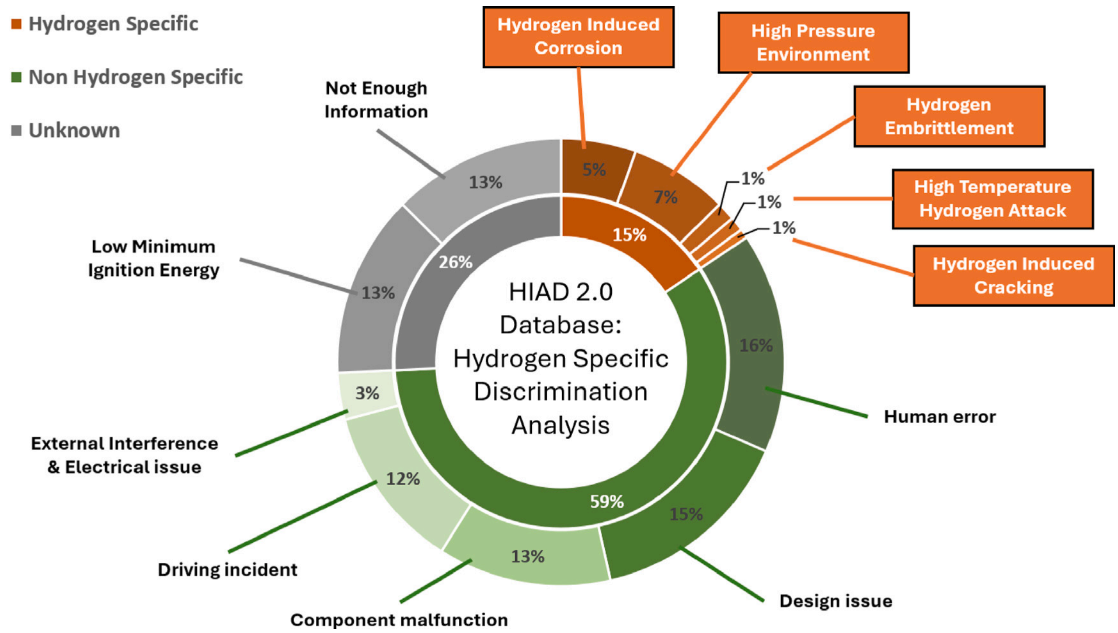

Fig. 1. Discrimination of the cause of incidents reported in hydrogen facilities in the HIAD 2.0 database up until 2024. The incidents are classified as Hydrogen-Specific, Non-Hydrogen-Specific, and Unknown in the inner circle depending on the nature of the cause and the information available. The outer circle further subdivides each general label into more detailed categories to emphasize the dominant causes reported.

of 500 kg of chlorine and an unknown quantity of hydrogen in a low-pressure circuit, forming an explosive mixture.

While the majority of the incidents stemmed from common industrial hazards unrelated to hydrogen's unique properties, this analysis highlights the general risks that are inherent in various industrial systems. These findings suggest that many of the challenges associated with hydrogen applications are not exclusive to hydrogen itself but are instead part of broader industrial safety considerations.

3. Hydrogen failure mechanisms

As hydrogen applications continue to expand and evolve, addressing the unique hazards associated with hydrogen becomes increasingly critical. A deep understanding of hydrogen-specific failure mechanisms is essential for identifying potential vulnerabilities and implementing effective mitigation strategies. These failure mechanisms stem from hydrogen's distinct interactions with materials and the high-pressure environments unique to hydrogen systems. Material failures, in particular, can manifest through mechanisms such as hydrogen embrittlement (HE), hydrogen-induced cracking (HIC), high-temperature hydrogen attack (HTHA), and hydrogen-assisted corrosion (HAC). A thorough exploration of these failure modes and the associated high-pressure hazards is necessary to fully grasp their implications, mitigate risks, and ensure the safe deployment of hydrogen technologies.

3.1. Hydrogen embrittlement

HE is a degradation process where hydrogen atoms interact with materials, causing a reduction in mechanical properties such as tensile strength, ductility, fatigue resistance, and increased crack propagation rates [62,63]. The steps of HE are schematically summarized in Fig. 2. In hydrogen-rich environments, hydrogen molecules dissociate into atoms near the metal surface. Atomic hydrogen subsequently enters the material's microstructure through adsorption or absorption (steps (A)–(B)). Adsorption is driven by the interaction between hydrogen and metal, and combines physical adsorption governed by van der Waals forces and chemical adsorption involving covalent bonding. Absorption, on the other hand, leverages the small size of hydrogen atoms to penetrate deep into the material's lattice structure.

Once inside the material, hydrogen atoms diffuse along lattice defects such as grain boundaries, dislocations, and voids, eventually accumulating in voids or spaces between non-metallic inclusions and the metallic matrix [64] (step (C)). The presence of hydrogen in these lattice defects deteriorates the mechanical properties of the material. While the exact mechanism remains under debate [63,65], three primary theories have received particular attention. The first, Hydrogen-Enhanced Decohesion (HEDE), suggests that hydrogen weakens metallic bonds near grain boundaries or dislocation cores, reducing interatomic cohesion. Such lower cohesion promotes brittle fractures, especially along grain boundaries, phase boundaries, or other interfaces [66,67]. The second, Hydrogen-Enhanced Localized Plasticity (HELP), suggests that hydrogen reduces the barriers to dislocation motion, facilitating dislocation slip or climb. This localized plastic deformation leads to stress concentration, ultimately causing brittle fractures [68]. Finally, the Adsorption-Induced Dislocation Emission (AIDE) theory states that hydrogen atoms adsorbed near crack tips alter local surface energy or cohesive strength, promoting dislocation emission and accelerating crack propagation [69]. All three mechanisms provide a realistic microscopic framework to explain the phenomena of hydrogen embrittlement, forming the theoretical foundation for this degradation process.

In the analyzed dataset, four incidents explicitly identified hydrogen embrittlement as the root cause (incidents ID 385, ID 196, ID 893, and ID 1047). Each of these cases involved hydrogen embrittlement-induced component failures, leading to hydrogen release. For example, a hydrogen fuel tank release caused a fire at an AC Transit fuel station on May 4th, 2012. The failure of a pressure relief valve resulted in the immediate release of approximately 30 kg of hydrogen in the first minute. This rapid release mixed with air in the vent tube, leading to ignition. After the pre-mixed gases were consumed, the venting hydrogen produced a jet flame from the vent outlet. The root cause of the incident was the use of incompatible materials in the pressure valve; specifically, inadequate 440C steel suffered embrittled by hydrogen service, causing the valve to malfunction.

3.2. Hydrogen induced cracking

HIC is a hydrogen-related damage mechanism predominantly observed in low- to medium-strength steels. It is characterized by crack

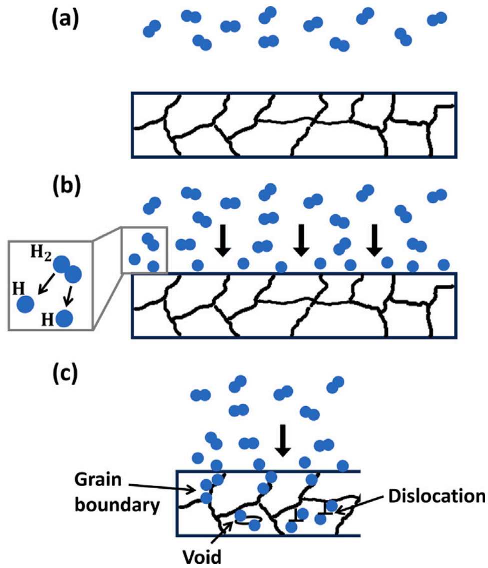

Fig. 2. Mechanisms and Processes of Hydrogen Embrittlement. (A) Exposure of metallic materials to a hydrogen-rich environment. (B) Surface adsorption and dissociation of molecular hydrogen (H_2) into atomic hydrogen (H). (C) Penetration of hydrogen atoms into the metal and interaction with microstructural defects.

propagation driven by internal pressures generated by the accumulation of hydrogen gas molecules within the cracks, even in the absence of external stress [70]. HIC typically occurs in wet or acidic environments, such as those containing hydrogen sulfide, and often manifests as cracks parallel to the steel surface. In some cases, it is accompanied by stepwise cracking or blistering, where surface bulges form due to high internal pressure.

Despite being distinctly defined in resources such as the ASM Handbook and NACE standards, HIC terminology remains inconsistent across academic and engineering literature [71]. It is often confused with HE due to their shared association with hydrogen-related material degradation. HE occurs when atomic hydrogen diffuses into the metal lattice, causing localized embrittlement and ductility loss under applied stress. In some cases, HE can be partially reversible if the hydrogen escapes from the material [72]. In contrast, HIC is primarily caused by the accumulation of molecular hydrogen at microstructural defects, such as inclusions, grain boundaries, or voids. The trapped hydrogen forms high-pressure bubbles, leading to internal cracking. Unlike HE, HIC does not require external stress and is generally irreversible.

The HIC process is illustrated in Fig. 3, which outlines its four distinct stages. The process begins in an acidic environment, where atomic hydrogen is absorbed on the metal surface and subsequently diffuses into the material's interior (similar to steps (A)–(B) of Fig. 2). As hydrogen atoms accumulate at microstructural defects – such as inclusions, voids, or grain boundaries – the local hydrogen concentration increases until it exceeds the material's solubility limit. At this stage, molecular hydrogen precipitates at these defects, forming high-pressure gas bubbles that exert internal stress (step (A)). With increasing pressure, cracks initiate and propagate due to this internal stress (step (B)). When cracks form near the material surface, the high-pressure hydrogen gas trapped within them can push the surface metal outward, resulting in blister formation (step (C)). HIC is more likely to occur in thin materials, which tend to develop shallow cracks, or in environments with high hydrogen concentrations and rapid hydrogen diffusion rates. Conversely, deeper cracks far from the surface typically lead to stepwise cracking. Both blistering and stepwise cracking originate from the same underlying formation mechanisms, with their specific manifestation depending on crack location and environmental conditions.

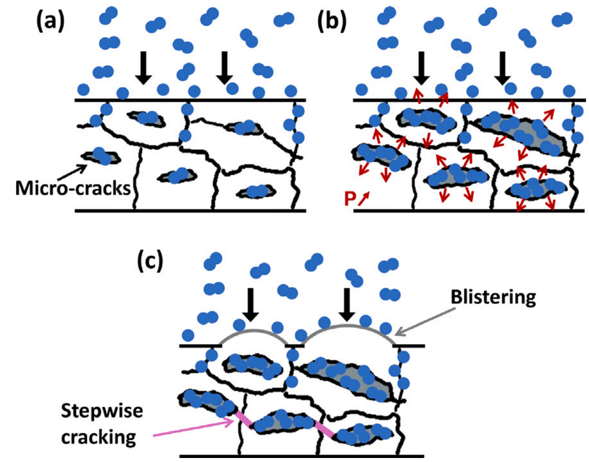

Fig. 3. Mechanisms and Progression of Hydrogen-Induced Cracking (HIC). (A) Hydrogen accumulation at microstructural defects, generating localized internal pressure. (B) Progressive hydrogen accumulation and pressure escalation, leading to crack enlargement. (C) Formation of stepwise cracking along the shortest paths between adjacent cracks and surface blistering in regions where cracks approach the material surface.

Three incidents in the dataset explicitly attribute material failure to HIC. The most recent incident, ID: 1057, occurred on March 7, 2022, in the United States and involved a hydrogen transmission pipeline failure caused by HIC. The initial cause was the complete failure of a pipe girth weld, likely within the heat-affected zone, due to hydrogen-induced cracking.

3.3. High temperature hydrogen attack

HTHA refers to the irreversible deterioration of the mechanical properties of carbon-containing metals or alloys when exposed to hydrogen at elevated temperatures [73–75]. HTHA significantly impacts hardness, strength, ductility, and impact toughness of a material due to the chemical reaction between hydrogen and carbon present in the steel or its microstructure as carbides, leading to the formation of methane (CH_4) [76]. A slight swelling can be recorded in certain cases [77]. The HTHA process can be broken down into several key stages.

At temperatures exceeding approximately 200 °C for carbon steel [77,78], hydrogen atoms dissociate and penetrate the metal's microstructure, as shown in Fig. 4(A). The diffusion rate increases with temperature and pressure, enabling hydrogen atoms to penetrate more easily [79]. The specific threshold temperature for HTHA initiation depends on various factors, including material composition, pressure, stress levels, and exposure duration. This stage shares similarities with the hydrogen embrittlement process discussed earlier. Once hydrogen atoms diffuse into the metal, they react with carbon present in the steel to form methane gas, as illustrated in Fig. 4(B). This reaction occurs predominantly along grain boundaries, where microscopic methane bubbles form. Because methane molecules are much larger than hydrogen atoms, they cannot diffuse out of the metal, resulting in significant pressure buildup. This internal pressure leads to the formation of voids or cavities at grain boundaries or other high-interface energy regions, such as inclusion surfaces. Cracks often develop during the growth and coalescence of methane bubbles (as shown in Fig. 4 (C)) [80]. As methane gas accumulates, internal pressure increases, forming microvoids and initiating cracks along grain boundaries. These internal stresses reduce the toughness and ductility of the material, making it more brittle. While hydrogen molecules may also exist in cavities, their size and pressure are generally much smaller than those of methane bubbles. The pressure exerted by methane can range from levels comparable to hydrogen (on the order of tens of MPa)

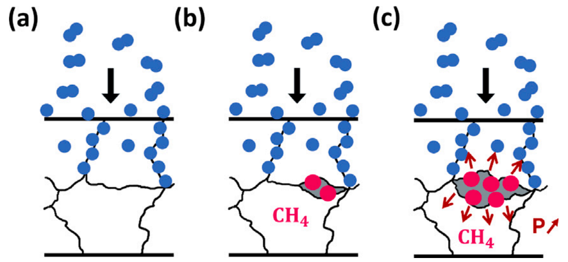

Fig. 4. Mechanism and process of high-temperature hydrogen attack. (A) Hydrogen are attracted to the metal surface, dissociate into hydrogen atoms, and diffuse into the metal. (B) Hydrogen atoms react with carbon within the metal to form methane (CH_4), leading to the formation of microcracks. (C) As methane accumulates inside the metal, internal pressure increases, causing cracks to grow larger over time.

up to two orders of magnitude higher, potentially reaching several GPa under extreme conditions [81]. The exact pressure depends on factors such as carbide stability, material microstructure, and hydrogen diffusion kinetics. Microcracks that form along grain boundaries rapidly propagate under mechanical stress, especially in equipment operating at high temperatures and pressures. Over time, the accumulation and expansion of these cracks compromise the structural integrity of the material, leading to catastrophic failure.

In the analyzed dataset, two incidents were attributed to high-temperature hydrogen attack (HTHA), accounting for approximately 1% of all recorded hydrogen-related failures. One of the most severe cases occurred on April 2, 2010, at a petroleum refinery in the United States. In this incident (ID 883), a catastrophic rupture of a heat exchanger in the catalytic reformer/naphtha hydrotreater unit (NHT unit) resulted from HTHA-induced material degradation. The failure led to the sudden release of highly flammable hydrogen and naphtha at over 500° F (260 °C). The released gases self-ignited, triggering an explosion followed by an intense fire that lasted for more than three hours. Tragically, seven employees (one shift supervisor and six operators) working near the heat exchanger at the time of the incident were fatally injured. The direct cause of this event was the degradation of carbon steel under prolonged exposure to high-temperature hydrogen, leading to seal failure and uncontrolled gas release.

3.4. Hydrogen-induced corrosion

While hydrogen itself is not inherently corrosive, its presence can significantly accelerate the corrosion process of metals and potentially lead to cracking [82]. Corrosion is an electrochemical process involving the anodic dissolution of metal and the cathodic reduction of species such as hydrogen ions [83]. The two electrodes, anode and cathode, typically exist on the surface of the metal, initiating the corrosion process.

As a typical example, the mechanism of H_2S-induced corrosion of iron is illustrated in the case of sulfur-containing environments in Fig. 5. The process typically begins with anodic and cathodic reactions on the metal surface (step (A)). Metal dissolution occurs at the anode where Fe is oxidized into Fe^{2+}. The electrons released during this process are transferred through the metal to the cathodic regions, where hydrogen ions H^+ are reduced to atomic hydrogen. However, the presence of H_2S inhibits these hydrogen atoms from combining into hydrogen molecules [84]. Instead, the Fe^{2+} ions produced at the anode react with HS^- or S^{2-} ions in the solution, forming mackinawite (FeS). Over time, a FeS film develops on the metal surface (step (B)). This protective film adheres to the surface and slows further metal dissolution. The corrosion typically manifests as pitting, a localized form of corrosion with small-diameter pits covered by corrosion products, making them difficult to observe [85]. However, the FeS film is unstable and porous, and its integrity can be compromised by environmental factors such as pH levels, temperature, and H_2S concentration (step (C)) [86]. Hydrogen also plays a critical role in this process. As H_2S reacts with iron, molecular H_2 accumulates at the metal-film interface, influencing the stability of the FeS layer. This accumulation of H_2 can weaken the protective FeS film, making it more prone to detachment and exposing fresh metal surfaces to further corrosion. This effect is particularly significant in high-pressure hydrogen environments, where increased hydrogen permeation enhances localized acidification, promoting pitting and accelerating anodic dissolution [87]. Defects in the film can lead to the persistence of localized corrosion [87]. Once pitting occurs, stress and the formation of occluded cells can result in stress corrosion cracking (SCC) [88]. Unlike HIC, SCC exhibits different crack propagation directions which is perpendicular to the tension direction [89]. Hydrogen atoms also accumulate at the crack tips, exacerbating anodic dissolution and accelerating the progression of SCC [90].

In pure hydrogen environments, corrosion is primarily influenced by the presence of impurities since hydrogen is not corrosive. While the exact mechanisms vary depending on the type and concentration of these impurities, the overall corrosion process follows well-established principles. Hydrogen plays a critical role in several key stages, including the degradation of protective films, acceleration of anodic dissolution, and increased susceptibility to localized corrosion. In hydrogen-rich conditions, protective films on metal surfaces can experience alterations in their composition and structure, compromising their effectiveness [82]. Additionally, hydrogen can enhance anodic reactions, leading to more rapid metal dissolution [91]. For pitting corrosion, the presence of hydrogen significantly increases susceptibility, particularly in duplex stainless steel, where higher hydrogen concentrations degrade pitting resistance [92]. Hydrogen also accumulates at crack tips, intensifying localized corrosion and promoting the progression of cracks as mentioned previously.

In the analyzed dataset, hydrogen-induced corrosion accounted for 5% of all recorded events. These incidents are associated with either sulfur-containing environments (e.g., H_2S, sulfuric acid) or pure hydrogen exposure, each accounting for approximately 50% of the total corrosion-related failures. Two illustrative incidents highlight hydrogen's effect in these environments. Incident ID 947 occurred on April 28, 2011, in France and involved a diesel hydrodesulfurization unit in a sulfur-containing environment where a release of aerosol hydrocarbons, hydrogen, and H_2S occurred from the reactor outlet within a cooling tower. The protective measures, including injecting nitrogen and venting to a flare, prevented ignition, but the underlying corrosion mechanism was consistent with H_2S-induced localized corrosion and cracking. In a pure hydrogen environment, Incident ID 384 occurred on January 16, 2008, in the United States, and details the premature failure of a pressure relief device on a hydrogen delivery tube trailer during refueling. The burst disk, made of Inconel 600, failed due to stress corrosion cracking (SCC) exacerbated by the synergistic effects of hydrogen exposure and working pressure. This incident underscores the critical importance of selecting appropriate materials for hydrogen service environments, where both hydrogen impurities and the hydrogen-rich environment itself can exacerbate corrosion and accelerate material degradation.

3.5. High pressure hydrogen environment

Hydrogen's unique physicochemical properties necessitate operation under significantly high pressures, setting it apart from conventional energy carriers. For example, as shown in Table 2, hydrogen storage systems typically operate at pressures ranging from 200 to 700 bar, significantly higher than the storage pressures for natural gas (200–275 bar) and other hydrocarbon gases. This reliance on high pressure arises from hydrogen's intrinsically low volumetric energy

Table 2
Pressure comparison of different gas energy carriers.

Gas Type	Hydrogen [93]	Nature Gas [94]	Propane [95]	Ethylene [96]	Gasoline Vapor [97]
Pressure (bar)	200 - 700	200 - 275	7 - 12	9 - 57	0.54 - 0.62

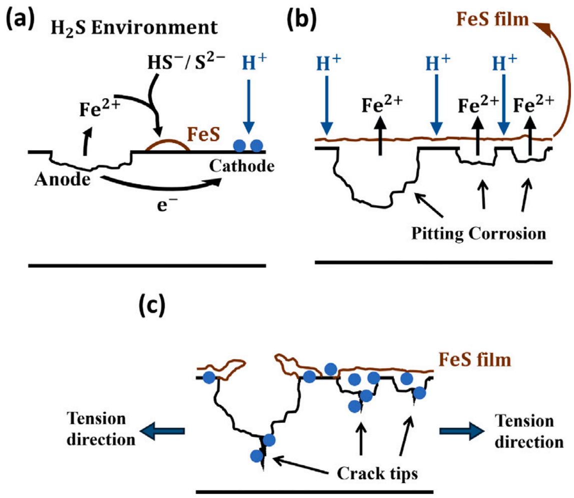

Fig. 5. Effect of hydrogen on corrosion processes: an example of H_2S corrosion. (A) Initial anodic and cathodic reactions forming FeS in a H_2S environment. (B) Development of porous FeS protective films. (C) Breakdown of FeS films exposing fresh metal surfaces and presence of crack tips in pitting corrosion.

density, which makes compression essential for enabling its use as a viable energy storage medium [98].

The increase in pressure not only facilitates hydrogen storage but also profoundly alters its behavior. Elevated pressure affects hydrogen's density, reduces its minimum ignition energy (MIE), and broadens its flammability limits. These changes, while essential for storage and application, create unique challenges for hydrogen systems. Unlike other compressed gases, hydrogen's molecular properties interact intricately with containment materials and system components, leading to complex failure mechanisms. Pressure acts as a critical parameter, significantly influencing the physicochemical properties and degradation behaviors of materials in hydrogen systems.

High-pressure environments accelerate hydrogen atom penetration into metal lattices, increasing the probability and severity of HE. Pressure affects both the solubility of hydrogen in metals and its diffusion behavior [99]. According to Henry'law, the solubility of hydrogen is positively correlated with the partial pressure of hydrogen gas [100]. As a result, the amount of dissolved hydrogen in metals increases significantly under high-pressure conditions. Moreover, higher pressure enhances the concentration gradient of hydrogen within the metal, thereby accelerating the diffusion process [101]. The combined effects of increased solubility and diffusion rate make it easier for hydrogen molecules to penetrate the metal under high-pressure conditions, significantly compromising the mechanical properties of the material [102]. Consequently, the fatigue life and damage resistance of metals are severely reduced in high-pressure hydrogen environments.

High-pressure environments also promote HIC. Higher hydrogen concentrations due to high pressure facilitate the aggregation of hydrogen molecules at material defects, leading to the formation of hydrogen bubbles [103]. These microscopic hydrogen bubbles gradually connect, creating stress concentration zones within the material, which can ultimately result in sudden fractures. In addition, higher pressures accelerate crack growth rates. The increased hydrogen concentrations driven by pressure reduce fracture energy, thereby facilitating crack propagation [104].

In the case of high-temperature hydrogen attack (HTHA), elevated pressure enhances hydrogen solubility and diffusion, promoting reactions with carbon within the steel matrix to form methane gas bubbles [75]. These bubbles disrupt the metal's microstructure, significantly reducing its strength and ductility.

Hydrogen-induced corrosion also intensifies under high-pressure conditions. Elevated hydrogen concentrations increase the permeability of protective oxide films, allowing hydrogen to react directly with base metals [105]. This accelerates corrosion rates and initiates a self-reinforcing cycle of oxide breakdown and hydrogen ingress. The interaction between corrosion media and metal surfaces becomes more aggressive under higher pressures, increasing the formation and detachment rates of corrosion products [106].

High-pressure hydrogen environments can not only accelerate mechanisms like HE, HIC, HTHA, and hydrogen-induced corrosion but also significantly impact stress conditions and material behaviors under repeated pressure variations. Elevated pressures intensify local stress concentrations, especially around defects, grain boundaries, and welds, while promoting hydrogen diffusion and trapping in these regions [107]. This weakens material strength, reduces ductility, and increases crack propagation rates. Repeated pressure fluctuations further exacerbate fatigue damage, initiating and accelerating crack growth from stress concentrators, particularly in high-stress areas. In hydrogen environments, the combination of elevated local stress concentrations and hydrogen induced failure mechanisms significantly shortens material lifespan, as changes enhance hydrogen penetration and amplify crack propagation, ultimately leading to premature material failure.

These theoretical risks are evidenced by real-world incidents. In the analyzed database, high-pressure-related incidents accounted for 7% of all cases. Firstly, the direct impact of high pressure on materials and equipment significantly increases the likelihood of failure. For example, at a hydrogen refueling station in Norway (incident ID 884, 2019), a gasket failed due to long-term fatigue under 900 bar pressure, resulting in a hydrogen leak and subsequent explosion. Similarly, at a chemical plant in France (incident ID 786, 2011), high pressure of 200 bar accelerated the propagation of cracks in a pipeline, ultimately leading to the formation of a vapor cloud and an explosion. Additionally, at a chemical plant in Switzerland (incident ID 844, 2017), a pressure-reducing device malfunctioned under an operating pressure of 300 bar, causing a hydrogen leak and fire. These incidents demonstrate that high-pressure environments not only accelerate material fatigue and aging but also pose significant reliability challenges to critical system components such as gaskets, welds, and other stress-concentration areas. Secondly, high-pressure environments create extreme localized stress in stress-concentration zones (e.g., welds and flange connections), which can lead to failure. For instance, in a syngas-related accident in Slovakia (incident ID 949, 2010), a flange seal shifted under 150 bar pressure, causing gas leakage and a subsequent fire. Similarly, during a hydrogen transport operation in the United States (incident ID 885, 2018), a pressure relief device (PRD) prematurely activated under high pressure due to inadequate rating, releasing a large amount of hydrogen and igniting a fire. In another case (incident ID 174), a high-pressure environment ranging from 240 to 280 bar caused excessive localized stress at a weld joint, leading to leakage. These incidents highlight how high pressure amplifies vulnerabilities in stress-concentration areas and increases the likelihood of accidents. Moreover, Rapid pressure differentials can destabilize equipment or cause widespread gas diffusion. For example, in one incident (incident ID 142, date unspecified), a system rapidly depressurized from 220 bar to 3 bar, creating internal stress imbalances that caused gasket failure and leakage. In another incident in France (incident ID 342, date unspecified), a high-pressure leak formed a vapor cloud, leading to an explosion that caused extensive damage to surrounding facilities. Similarly, in another case (incident ID 382, 173 bar), pressure fluctuations during depressurization caused system instability, further escalating the severity of the incident. These cases show that rapid depressurization not only triggers equipment failures but also magnifies the impact of incidents through leakage and diffusion.

3.6. Chemical distinctiveness of hydrogen-induced hazards

The previous sections 3.1 to 3.5 have examined individual failure mechanisms in detail, focusing on how hydrogen affects material integrity through processes such as embrittlement, cracking, high-temperature degradation, corrosion, and high-pressure effects. While these physical mechanisms have been analyzed separately, their common chemical basis requires explicit discussion to fully convey the real-world implications of hydrogen safety. Unlike hydrocarbons, where containment failure modes are predominantly characterized by thermal or mechanical processes, hydrogen exhibits direct chemical interactions with materials. These interactions lead to material degradation pathways that are fundamentally different from those observed when materials used for containment interact with other gaseous fuels.

In high-temperature environments, hydrogen reacts with carbides within steels to form methane (HTHA). For instance, the presence of iron carbide Fe_3C in steel can lead to the effective reaction [108]:

$$Fe_3C + 4[H] \rightarrow CH_4^{gas} + 3Fe \quad (1)$$

This reaction, which causes irreversible void formation and crack propagation, would not occur in conventional hydrocarbon containment systems. At the microstructural level, HIC arises from the accumulation and recombination of molecular hydrogen at inclusions or grain boundaries, creating high-pressure bubbles even in the absence of external stress, a behavior rarely seen with other gases [70]:

$$2[H] \rightarrow H_2^{gas} \quad (2)$$

Furthermore, in electrochemical processes, hydrogen accelerates anodic dissolution and destabilizes protective surface films, significantly promoting localized corrosion and stress corrosion cracking. As illustrated in 5, the presence of a H_2S environment over Fe generates a porous protective FeS layer [83,109]:

$$Fe^{2+} + HS^- \rightarrow FeS^{solid} + H^+ + e^- \quad (3)$$

The released hydrogen ion H^+ can diffuse through the FeS film and support the development of cracks in the metal surface. In contrast, hydrocarbons have minimal chemical affinity with metallic surfaces. These chemically driven mechanisms, further amplified by hydrogen's high diffusivity and high-pressure service conditions, represent failure modes inherently specific to hydrogen containment systems.

4. Linking hydrogen properties to past incidents

Beyond the comparison of hydrogen properties with those of other common gaseous energy carriers, integrating the past incidents analysis helps pinpoint the specific properties that pose challenges to the industry.

4.1. Small molecular size and high pressure

The small molecular size of atomic hydrogen (53 pm) allows it to easily diffuse into metallic structures. As previously shown, the diffusion of atoms of hydrogen through the lattice of a metal container is the first step in the processes of HE, HTHA, and HIC. The hydrogen diffusivity in different steel samples has been reported in the literature, with room temperature values ranging from 1.5×10^{-7} cm^2 s^{-1} to 2×10^{-5} cm^2 s^{-1} for X65 steel, a high-strength, low-alloy steel commonly used in pipelines [110].

In contrast, natural gas, propane, ethylene, and gasoline vapor all feature lower molecular diffusivity values through a metallic lattice that are negligible. This can be explained by the difference of two orders of magnitude in molecular size, ethylene being the closest species with a molecular size of about 400 pm [111]. To prevent molecular diffusion of hydrogen in steel, present research work investigate the performance of protective coatings on the steel surface [112]. Using materials with low hydrogen solubility and diffusivity such as graphene, coatings can shield the steel from hydrogen permeation. Additionally, due to its small molecular size, hydrogen has a much lower density compared to other gases. To compensate for this low density and improve storage and transportation efficiency, hydrogen is often handled under high-pressure conditions. However, high-pressure environments further increase the risk of material failure.

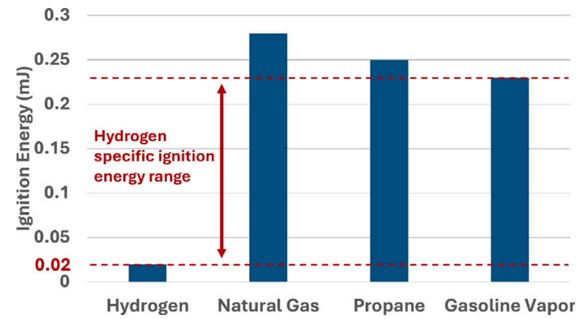

Fig. 6. Minimum ignition energy of hydrogen and other common gaseous energy carriers, data from [114].

4.2. MIE

Regarding its low MIE, it is challenging to determine whether this is unique to hydrogen, as the energy of the ignition source is uncertain. Based on incidents involving low-energy ignition sources, the energy range of electrostatic discharge may indeed fall between the MIE of hydrogen and that of other common gases as indicated in Fig. 6. The energy of electrostatic discharge can be inferred from Eq. (4), where the discharge energy E depends on voltage V and capacitance C. Voltage and capacitance depend on the method of generation and storage. When the capacitance is small, such as for small objects (e.g., particles mixed with hydrogen) with very low capacitance, combined with low-voltage conditions (e.g., slight friction), it is possible to generate energy between 0.02 mJ and 0.23 mJ [113].

$$E = \frac{1}{2}CV^2 \quad (4)$$

Another important aspect is the combined effects of hydrogen's properties. For instance, as mentioned in Section 2.2, hydrogen accumulation is linked to its large flammability range, and its low MIE further facilitates incident occurrence. Similarly, high pressure itself cannot cause incident directly. However, as noted in Section 3.5, when combined with other hazards, it significantly escalates the likelihood of accidents. Although incidents rarely mention it, theoretically, high pressure could lead to the reverse Joule–Thomson effect, resulting in a heating effect that might promote hydrogen's self-ignition [5].

Incidents classified as "Unknown" in the dataset primarily stem from two factors: not enough information and characteristics related to hydrogen's Minimum Ignition Energy (MIE). Among these, 12% of incidents are attributed to missing information, while 15% are associated with hydrogen's MIE, highlighting its significance in accident analysis.

Hydrogen's MIE is an order of magnitude lower than that of common gaseous energy carriers, as shown in Fig. 6. This characteristic makes hydrogen highly sensitive to low-energy ignition sources. Determining whether an incident is specific to hydrogen requires assessing whether the ignition source's energy falls below the MIE threshold for other gases. In hydrogen-related fires and explosions, the ignition source is often difficult to identify and record. Consequently, many incidents are reasonably attributed to self-ignition [115]. However, the mechanisms of high-pressure hydrogen self-ignition remain poorly understood. Current theoretical hypotheses include the reverse Joule–Thomson effect, electrostatic ignition, diffusion ignition, sudden adiabatic compression, hot surface ignition, and mechanical friction and impact [5].

The dataset reveals key ignition-related terms that help identify incidents potentially caused by hydrogen's low MIE. These terms include "electrostatic discharge", "sparks", and "electrical sources". These ignition sources are interconnected. For instance, friction can generate static electricity through interactions with surfaces or particles, leading to electrostatic discharge. If the discharge generates sufficient heat, it can ignite hydrogen, resulting in a fire or explosion. Electrical sources, such as arcs in equipment, can directly produce enough heat to ignite hydrogen and may also generate sparks. Sparks, in turn, can result from electrostatic discharge, electrical sources, or mechanical impacts. In some incidents, the specific origin of sparks remains unclear, adding complexity to the analysis.

For example, in a 2020 incident at a solvent production facility in China (Event ID 810), hydrogen flowing through a pipeline containing solid particles generated static electricity through friction with the pipe walls. The resulting electrostatic discharge ignited the hydrogen. Although friction played a role, the ultimate ignition source was the electrostatic discharge. Similarly, in a 2022 high-pressure hydrogen leakage incident in Italy (Event ID 249), hydrogen leaked and mixed with air in a vent pipe, forming a near-stoichiometric mixture. The friction-generated electrostatic discharge subsequently triggered an explosion. These incidents underscore the critical role of electrostatic discharge as a low-energy ignition source in hydrogen-related accidents.

Electrical sources also play a significant role in some incidents. For instance, in a 2022 fire at a hydrogen refueling station in South Korea (Event ID 1018), although the exact origin of the spark was not recorded, a design flaw in the equipment connectors likely caused an electrical spark, igniting the hydrogen. This highlights the importance of heat generated by electrical sources in hydrogen-related incidents.

Some incidents involve hydrogen accumulation and the potential reduction in MIE of mixed gases. When hydrogen mixes with other gases, such as air or methane, the overall MIE of the mixture may decrease, increasing the risk of ignition. However, due to a lack of detailed records on mixing ratios and accumulation levels, it is challenging to determine whether such incidents are unique to hydrogen. For example, in the 2022 incident in Italy (Event ID 249), hydrogen leaked and mixed with air, forming an explosive near-stoichiometric mixture, which was subsequently ignited by electrostatic discharge.

These cases illustrate that electrostatic discharge and sparks are primary mechanisms for low-energy ignition, closely linked to hydrogen's low MIE characteristics. While hydrogen accumulation and mixed-gas risks are common in incidents, they are not necessarily unique to hydrogen. More detailed data on ignition sources, mixing ratios, and accumulation conditions are needed to distinguish hydrogen-specific hazards from those of other flammable gases.

5. Prevention related to hydrogen induced damage in pipeline

Among the incidents identified as hydrogen-specific, a majority (56%) is associated with pipelines. With the growing emphasis on integrating hydrogen into broader applications, the role of pipelines in hydrogen transport becomes increasingly critical. Particularly for large-scale, long-distance transport exceeding 500 km, pipelines emerge as a more cost-efficient and environmentally sustainable method for hydrogen delivery compared to alternative means [116].

In traditional industries such as petrochemical and chemical sectors, hydrogen's role as an industrial feedstock is well-established. As a result, small-scale hydrogen transport systems in these industries are relatively mature. However, large-scale hydrogen transport has been less common historically. Moreover, due to the relatively underdeveloped hydrogen transport network compared to natural gas, blending hydrogen into existing natural gas pipelines has emerged as a cost-effective transitional strategy. This approach leverages existing infrastructure, facilitating hydrogen adoption while minimizing initial investments [117].

Regardless of the purity of hydrogen in a pipeline network, the hazards identified in this study provide valuable insights for optimizing hydrogen transport systems. These insights form the basis for discussions on improving the safety and efficiency of hydrogen transport.

Material failure

The selection of materials for hydrogen systems already considers key factors such as resistance to HE, impermeability to hydrogen, corrosion resistance, high strength, and toughness. These considerations are detailed in hydrogen safety standards like ISO/TR 15916 and ASME B31.12 [118], with the latter being the most widely recognized standard for hydrogen pipeline systems. However, the hazards identified in this study highlight critical risks associated with hydrogen pipeline transport. As previously discussed, the varying mechanisms through which hydrogen damages materials remain partially ambiguous. A rigorous classification of these mechanisms is necessary to propose targeted prevention strategies. While research has extensively focused on HE, the other three (HIC, HTHA and hydrogen-induced corrosion) have received comparatively less attention. This imbalance in research emphasis affects several aspects, including material selection, lifespan evaluation, and monitoring strategies.

For material selection, although hydrogen-impermeable materials are prioritized, their performance under specific environmental conditions (such as the presence of impurities, pressure, and temperature) affects the manifestation and progression of these hazards. For instance, high pressure exacerbates hydrogen permeability, increasing susceptibility to HE and HIC. While typical hydrogen pipeline operations may not reach temperatures that trigger HTHA, understanding the interaction between material composition, pressure, and temperature is crucial, as high-pressure and high-carbon materials can experience HTHA at lower temperatures [75]. Additionally, impurity control is critical for mitigating hydrogen-induced corrosion, especially in blended hydrogen-natural gas environments where impurities like H_2S and CO_2 are present [119]. Conversely, some impurities have shown potential in reducing fatigue growth rates in pipeline materials, particularly by mitigating hydrogen-assisted degradation [120]. Understanding the dual role of impurities in promoting and inhibiting damage highlights the need for a comprehensive evaluation of mechanisms when selecting materials. Apart from the corresponding environmental factors, the materials currently available for hydrogen pipelines are limited, particularly those with high strength, excellent hydrogen resistance, and low cost [121]. From the perspective of material optimization, understanding these mechanisms is essential for optimizing material design.

Differentiating the primary mechanisms of material degradation not only facilitates more accurate lifespan predictions but also helps prioritize research efforts. Evaluations of material durability rely on a robust understanding of the relevant hazards. For example, HE mechanisms remain incompletely understood due to the coexistence of multiple hydrogen embrittlement mechanisms within steel [122]. Identifying the dominant mechanism is both a challenging and pivotal task. Similarly, hydrogen's role in corrosion processes, from altering protective films to accelerating anodic degradation, requires detailed exploration to improve corrosion prediction models [82,123]. By integrating an understanding of these mechanisms and their interactions, it is possible to refine existing predictive models and optimize material design and operating conditions to address the complex realities of pipeline applications.

Monitoring strategies also benefit from a deeper understanding of hydrogen-related hazards. ASME B31.12 encourages the use of non-destructive testing (NDT) techniques such as ultrasonic testing, acoustic emission monitoring, and magnetic particle inspection. Understanding the mechanisms of hydrogen-related damage helps clarify monitoring objectives and guide the selection of appropriate technologies, focusing on the most vulnerable areas. For example, corrosion, which involves material loss, can be monitored using resistance probes and electrochemical sensors. In contrast, cracks caused by HIC require acoustic methods or ultrasonic techniques. Ultrasonic technologies are versatile in detecting both corrosion and hydrogen-induced cracks, but their processes differ based on the target [124]. For instance, HE induces subtle lattice stress concentrations, necessitating optimization of acoustic emission systems to detect low-frequency signals. In HTHA, methane bubble formation creates microcracks, requiring ultrasonic systems with high resolution to identify these minute bubbles. Furthermore, monitoring intervals and strategies should be adjusted according to the different hazards identified, enabling timely detection and intervention.

The role of high pressure in hydrogen transmission

The transportation of hydrogen as an energy carrier differs significantly from its traditional role as an industrial feedstock, particularly as efforts intensify to replace natural gas. From an energy perspective, hydrogen's volumetric energy density at ambient temperature is around one-third that of natural gas. As the hydrogen content in a gas mixture increases, the average calorific content decreases, requiring larger volumes of gas to meet equivalent energy demands. However, as flow rates are increased to maintain comparable energy density while reducing temperature gradients, pressure drops can occur [117]. This may cause delivery challenges, especially if the minimum required delivery pressure at the end-user is not met. Enhancing compression capacity is one approach to mitigate pressure drops, but this comes at the cost of increased environmental pressure.

Higher operating pressures not only pose technical limitations for compressors but also create conditions that amplify hazards, affecting material lifespan. The parameters influencing hydrogen-induced material damage remain incompletely understood, with primary research focusing on the interaction between hydrogen and material interfaces, the determination of critical concentrations, the quantitative description of dynamic diffusion processes, and the understanding of long-term behaviors [125]. These considerations are predominantly centered on hazards like HE and HIC, as they represent key mechanisms for hydrogen permeation and diffusion-induced micro-damage. However, compared to HE and HIC, relatively little is known about the effects of high pressure on hydrogen-induced corrosion [82].

From a safety perspective, a more detailed understanding of how pressure influences the mechanisms of various hazards is crucial. For instance, increasing pressure enhances hydrogen permeability, accelerating the initiation and propagation of HE and HIC. High pressures also amplify the interaction between hydrogen and material surfaces, potentially triggering microstructural damage that may remain undetected in initial stages. Hydrogen-induced corrosion, particularly under conditions of elevated pressure, remains poorly characterized but may play a significant role in the degradation of pipeline materials, especially in environments with impurities.

Balancing safety and energy demand requires a careful evaluation of the pressures and flow rates adopted for hydrogen transport. Pressure selection must consider not only the technical requirements for energy delivery but also the potential impact on hazard mechanisms. This balance ensures the optimization of pipeline performance while minimizing risks to material integrity and system reliability.

Ignition sources and electrostatic discharge

While incidents related to ignition sources were classified as "unknown" in this analysis, their significant proportion warrants attention as a potential risk. Among these, electrostatic discharge has been identified as a key factor. Pure, particle-free gases moving at high speeds generate little to no static charge. However, when the moving gas is contaminated with small amounts of solid particles or liquid droplets, static charge can be generated [7]. Particle motion across surfaces is a common source of static electricity, often caused by triboelectric charging [126]. Charge accumulation occurs when the rate of charge generation exceeds the rate of dissipation [127].

Common preventive measures for electrostatic discharge include grounding and bonding, flow velocity control, and humidity regulation. According to EIGA Doc 121/14 and ISO 19880-1, grounding resistance is typically required to be below 10 Ω. Lower grounding resistance allows for faster dissipation of static charges, ensuring rapid decay of electrostatic voltage and reducing the likelihood of charge accumulation that could lead to discharge. In contrast, natural gas systems are generally less stringent, with NFPA 77 recommending grounding resistance below 25 Ω and below 10 Ω in hazardous zones. This discrepancy highlights a potential risk when using natural gas pipelines for hydrogen transportation.

Flow velocity control is another critical measure. ISO 19880-1 recommends a flow velocity limit of less than 20 m/s for hydrogen transport to minimize static charge buildup caused by friction. In contrast, NFPA 77 allows natural gas flow velocities of 20–25 m/s, depending on pipeline materials and operating conditions. However, as mentioned earlier, the low volumetric energy density of hydrogen often necessitates higher flow rates to meet energy delivery demands. This creates a trade-off between safety and energy transport efficiency that must be carefully considered.

Humidity management is also a key factor, as lower humidity levels increase the likelihood of static charge accumulation. ISO 19880-1 recommends maintaining an ambient humidity above 50% for hydrogen pipelines, with strict humidity controls in place. For natural gas, NFPA 77 suggests maintaining humidity above 40%. Hydrogen facilities are often recommended to be outdoors to allow rapid dispersion in case of leaks, reducing the risk of hydrogen accumulation. However, outdoor environments make controlling humidity challenging. Monitoring systems should be implemented, and particular attention must be given to mitigating static hazards in low-humidity conditions.

Addressing these electrostatic hazards requires balancing operational safety with the practicalities of hydrogen transport. While stricter requirements for hydrogen systems compared to natural gas are justified, understanding and managing these hazards is crucial for minimizing risks in pipeline applications.

Conclusion

Hydrogen's unique physicochemical properties have long distinguished it from other commonly used gaseous energy carriers. By analyzing the HIAD 2.0 database, this study systematically discriminates hydrogen-specific hazards from potential issues, based on real-world hydrogen-related incidents. Focusing on the root causes of accidents, the analysis reveals that only 14% of reported incidents are hydrogen-specific, while 59% are similar to those observed with other gaseous energy carriers. Additionally, 15% of incidents could be related to hydrogen's low minimum ignition energy, though relevant data is missing to conclude. Among the hydrogen-specific incidents, this study identifies key hazard types, including hydrogen embrittlement, hydrogen-induced cracking, high-temperature hydrogen attack, hydrogen-induced corrosion, and high-pressure effects. By examining the mechanisms underlying these hazards, the analysis highlights critical challenges posed by hydrogen's intrinsic properties. This mechanistic understanding provides valuable insights into addressing core issues unique to hydrogen. Using hydrogen pipeline transport as a case study, this research offers recommendations for mitigating risks. Material selection, lifespan prediction, and monitoring strategies must account for the full spectrum of identified hazards, rather than focusing solely on hydrogen embrittlement, which has received a lot of attention. Furthermore, the conditions for hydrogen transport – such as pressure and flow velocity – must prioritize safety, taking into account the influence of increased pressure and flow rates on various hazard mechanisms. This study points out the importance of a targeted, mechanism-based approach to hydrogen safety. By integrating lessons from past incidents and emphasizing hydrogen-specific properties, future research and safety protocols can be better aligned to ensure the safe and efficient use of hydrogen as an energy carrier.

CRediT authorship contribution statement

Yutao Li: Writing – original draft, Visualization, Validation, Formal analysis. **Jose Torero:** Writing – review & editing, Validation, Supervision, Conceptualization. **Augustin Guibaud:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

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 material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.151155.

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