Computers and Chemical Engineering 173 (2023) 108199

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Lessons learned from HIAD 2.0: Inspection and maintenance to avoid hydrogen-induced material failures

Alessandro Campari [a,*], Antonio Javier Nakhal Akel [b], Federico Ustolin [a], Antonio Alvaro [c], Alessandro Ledda [d], Patrizia Agnello [d], Pietro Moretto [e], Riccardo Patriarca [b], Nicola Paltrinieri [a]

[a] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2b, Trondheim 7034, Norway
[b] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, via Eudossiana 18, Rome 00184, Italy
[c] SINTEF Industry, SINTEF, Richard Birkelands vei 2b, Trondheim 7034, Norway
[d] Department of Technological Innovations and Safety of Plants, Products and Anthropic Settlements, Italian National Institute for Insurance against Accidents at Work INAIL, via Roberto Ferruzzi 38, Rome 00143, Italy
[e] Joint Research Center JRC, European Commission, Westerduinweg 3, Petten 1755 LE, Netherlands

ARTICLE INFO

Keywords:
Data accident analysis
Business intelligence
Safety management systems
Hydrogen embrittlement
Process safety
Hydrogen safety

ABSTRACT

Hydrogen has the potential to make countries energetically self-sufficient and independent in the long term. Nevertheless, its extreme combustion properties and its capability of permeating and embrittling most metallic materials produce significant safety concerns. The Hydrogen Incidents and Accidents Database 2.0 (HIAD 2.0) is a public repository that collects data on hydrogen-related undesired events mainly occurred in chemical and process industry. This study conducts an analysis of the HIAD 2.0 database, mining information systematically through a computer science approach known as Business Analytics. Moreover, several hydrogen-induced material failures are investigated to understand their root causes. As a result, a deficiency in planning effective inspection and maintenance activities is highlighted as the common cause of the most severe accidents. The lessons learned from HIAD 2.0 could help to promote a safety culture, to improve the abnormal and normal events management and to stimulate a widespread rollout of hydrogen technologies.

1. Introduction

The fuel of the future should be versatile, efficient, environmentally friendly, affordable, and safe (Vezirolu and Barbir, 1992). In light of this, hydrogen has the potential to outclass its competitor fuels and thus has been recently promoted by the European Commission as one of the most promising solutions to minimize greenhouse gas emissions (European Commission, 2018). The increasingly widespread rollout of hydrogen is reflected by its expected share in the global energy scenario: 0.1% in 2020 (International Energy Agency, 2021a), 2% in 2030, and 10% in 2050 (International Energy Agency, 2021b). Nevertheless, one of the major bottlenecks for a massive application of hydrogen is represented by the safety aspects: along with its broad flammability range and its explosion potential (Sánchez and Williams, 2014), the capability of permeating and embrittling most of the containment materials makes its transportation and storage challenging (Abohamzeh et al., 2021). In fact, hydrogen-induced material damages are still responsible for several equipment failures and consequent releases of hazardous substances (Khare et al., 2017; Woodtli and Kieselbach, 2000). These safety issues must to be addressed with specific preventive strategies, such as inspection and maintenance activities aimed at guaranteeing the physical integrity and the fitness for service of equipment operating in a hydrogen environment (Campari et al., 2022a), along with mitigation strategies. Hydrogen-induced material degradations, also referred as Hydrogen Damages (HDs), could negatively affect the mechanical properties of a variety of materials and may result in failures, also of equipment which are not directly exposed to pure hydrogen (Ustolin et al., 2020b). It is proven that 99% of equipment breakdowns are preceded by certain signs that a failure or accident is going to occur; if correctly and timely detected, such failure precursors would allow the application of efficient maintenance planning and the implementation of appropriate preventive measures against accidental releases of hazardous substances (Geitner and Bloch, 2012). In fact, the likelihood of undesired events could be dramatically reduced through prevention (e.g., proper inspection and maintenance activities) (das Chagas Moura et al., 2015; Leoni et al., 2021).

---

[*] Corresponding author.
E-mail address: alessandro.campari@ntnu.no (A. Campari).

https://doi.org/10.1016/j.compchemeng.2023.108199
Received 8 November 2022; Received in revised form 13 February 2023; Accepted 20 February 2023

A beneficial strategy used to improve safety for specific industrial fields refers to the usage of the lessons learned from past accidental scenarios (Weiner et al., 2007). This strategy has been largely adopted, for instance, in the chemical and petrochemical industries (Paltrinieri et al., 2012; Tamascelli et al., 2022). Moreover, in the case of hydrogen-related process systems, the amount of data necessary to obtain probabilities of failure for hydrogen-specific components cannot be provided due to their low market penetration. In addition, the limited operational experience with this energy carrier hinders the achievement of the required fundamental knowledge around hydrogen-related accidents, incidents, and near-misses. Hence, safety reporting systems collecting and structuring available information on hydrogen-related accidents and failures are of the utmost importance to maximize the lessons learned from previous events and to develop effective preventive strategies. Later, these strategies can be implemented in new guidelines and regulations specifically tailored for hydrogen technologies. In this perspective, Hydrogen Incidents and Accidents Database (HIAD) was designed as part of the European Commission-funded Network of Excellence on Hydrogen Safety (HySafe) by the Joint Research Center (JRC) in 2006 (Kirchsteiger et al., 2007) and upgraded to HIAD 2.0 in 2017 (Melideo et al., 2019).

Given these bases, this study presents the results of consistent and systematic analyses of 628 undesired events reported in HIAD 2.0. Business Analytics (BA) techniques have been used as computing and information services technologies to mine data distributed across the events, transforming them into information useful to obtain an understanding of previous events, and empower flexible and advanced analyses (Benson et al., 1989; Nakhal et al., 2021a). BA has the potential to improve the decision-making process by integrating different data sources into a single environment for safety analysis (Patriarca et al., 2016), even in case of large datasets. The application of BA is still relatively novel in Safety & Process Management Systems (Nakhal et al., 2021a, 2021b; Wu et al., 2014). This tool has never been used to analyze the HIAD 2.0 database or to mine information from any other repository of hydrogen-related undesired event reports. This approach enables a systematic and automatic analysis of the accidents in terms of application stage, temporal and geographical distribution, causes and consequences. The dynamic and user-friendly interface allows for rapidly screening the information collected by the database and for mining data efficiently. Moreover, the model developed can be easily updated with additional records by simply modifying the source database. Further incident reports included in HIAD 2.0 are automatically provided to the BA data model, thus enabling continuous learning from past events to improve safety management in every stage of the hydrogen value chain. This dynamic analysis is a continuous process of identifying hazards, determining risk, suggesting preventive strategies to mitigate risk, monitoring, and reviewing the process by considering new knowledge from the increasing operational experience in this technological field (Khan et al., 2016; Paltrinieri et al., 2013). Despite the importance of inspection and maintenance activities to guarantee integrity and fitness for service of hydrogen equipment or hydrogen-related industrial processes, an effective policy for planning preventive safety measures for hydrogen technologies is still not available. The lack of previous studies on this domain is reflected by the absence of regulations, codes, and standards (Campari et al., 2022a). In this regard, the article aims to provide an essential contribution with the perspective of learning about different past accidents involving equipment for handling and storing gaseous and liquid hydrogen. The lessons learned from the analysis of HIAD 2.0 may also be used as a basis for risk assessments in the chemical and process industry and as an input to inform researchers and industrial stakeholders about promoting and developing a safety culture in their organizations.

The paper is structured as follows. The “Overview of accidents databases and previous analyses” section is a summary of the most relevant works regarding the lessons learned from previous events in various industrial fields, the available databases of hydrogen-related accidents, and the existing regulatory system regarding incident and accident reporting. Then, “Exploring HIAD 2.0” section provides a brief overview of the structure of the database HIAD 2.0. In addition, the “Methodology” section aims to explain step by step the approach adopted in this work, while the “Results” section summarizes the study of the database through the creation of BA solution to perform a descriptive analysis of the main findings. Toward the end, the “Discussion” provides a thorough analysis of the reports highlighting their root and secondary causes and formulates safety recommendations to avoid or prevent similar accidents in the future. The focus has been placed on losses related to the material failures of equipment operating in a hydrogen environment and incidents resulting from the lack of effective inspection and maintenance programs. Finally, the “Conclusion” summarizes the outcome of this work, as well as limitations and strengths linked to BA for managing safety data, with the intention to foster future research in the area.

2. Overview of accidents databases and previous analyses

A variety of structured databases and repositories for major accidents are already publicly available for several industrial sectors and societal activities. The French database Accident Reporting Information Analysis (ARIA) (BARPI, 2022), created by the Bureau for Analysis of Industrial Risks and Pollutions (BARPI) of the Ministry of Environment, collects all types of incidents, accidents, and near-misses which are deemed as dangerous to human health, environment, or public safety occurred worldwide over several decades. The French Authority for Nuclear Safety maintains a public list of all its investigations of nuclear accidents (ASN, 2022). The European Major Accident Reporting System (eMARS) (European Commission, 2020), provided by the Major Accident Hazards Bureau (MAHB) of the European Commission’s Joint Research centre, includes chemical accidents and near-misses covered by the Directive 2012/18/EU, also known as Seveso III Directive. In the UK, the former Institution of Chemical Engineers created a database (IChemE, 2022) containing brief summaries of industrial undesired events that occurred worldwide; the database was online between 1997 and 2000, but the events’ reports are still available. In Japan, the Institute for Advanced Industrial Science and Technology developed the Relational Information System for Chemical Accidents Database (RISCAD) (AIST, 2022) to collect industrial accidents, but it is currently unavailable to the public. The Japanese repository named Accident and Disaster Information Center (ADIC) (CRED, 2022) contains any type of undesired event that occurred in Asia. In the US, the Occupational Safety and Health Administration (US OSHA, 2022), the Chemical Hazard Investigation Board (US CSB, 2022), the National Transportation Safety Board (US NTSB 2022), and the Nuclear Reactor Commission (NRC, 2022) maintain public lists of all their investigations of accidents, providing the description and the causal factors.

Historically, several incidents’ databases and accidents reporting systems have been analyzed to learn from the past and better understand the undesired events that already occurred in a variety of industrial fields, preventing them from being repeated. For instance, Capelli-Schellpfeffer et al. (Capelli-Schellpfeffer et al., 1998) examined 500 electrical incidents to highlight the benefits of heavily populated accident databases to improve process safety. Yoon et al. (Yoon et al., 2000) proposed a quantitative method to support decision-making in prioritizing safety-relevant investments and avoiding most of the possible hazards. In particular, the authors considered more detailed classification beyond frequency and severity when assessing the risk. In 2000, Carol et al. (Carol et al., 2000) analyzed several undesired events that occurred in the chemical process industry (reported in Major Hazard Incident Data Service and Marsh-McLennan Report) with a focus on the economic assessment of accidents by applying update rates of industrial prices. Kirchsteiger (Kirchsteiger, 2001) applied a quantitative method to assess the frequency of major industrial accidents in Europe. Analyzing the abovementioned eMARS database, the author concluded that the 419 events reported following the Directive 96/82/EC, also known as Seveso II Directive, are not sufficient to come to reliable conclusions regarding their frequency. Keren et al. (Keren et al., 2003) developed a decision-making procedure to prioritize the improvement of selected processes or equipment employing component reliability databases. Uth and Wiese (Uth and Wiese, 2004) analyzed the major accidents reported in the German ZEMA database that occurred from 1993 to 1999. A root cause analysis pointed out the relevance of maintenance activities, knowledge of chemicals involved, and human factors. Sepeda (Sepeda, 2006) examined the Process Safety Incident Database (PSID) developed by the Center for Chemical and Process Safety (CCPS) and underlined how databases can benefit process safety in accident prevention. Bell and Healey (Bell and Healey, 2006) carried out a thorough literature review of four databases for major hazard accidents intending to identify the root causes and the control measures that would have prevented the undesired events reported. Charvet et al. (Charvet et al., 2011) conducted a Probabilistic Safety Assessment (PSA) of a facility for the distribution of Liquefied Petroleum Gas (LPG), focusing on the Boiling Liquid Expanding Vapor Explosion (BLEVE) scenario. The application of the PSA method demonstrated that the databases did not provide enough data for the equipment reliability evaluation. Therefore, the authors' institution initiated the collection of relevant information to provide failure rates for safety equipment in LPG plants. He et al. (He et al., 2011) highlighted the drawbacks of accident databases for the chemical industry in China. To develop a more effective information system, the authors collected and analyzed 976 major industrial accidents recorded in China over the last 40 years. In a report of the European Commission, Christou and Konstantinidou (Christou and Konstantinidou, 2012) analyzed 6183 accidents, incidents, and near-misses in the oil and gas sector from 1975 that are collected in the World Offshore Accident Database (WOAD) (DNV, 2012). They provided statistical results and lessons learned from these events. In 2013, Kidam and Hurme (Kidam and Hurme, 2013) analyzed the Japanese Failure Knowledge Database (FKD) to determine the causes for incidents triggered by equipment failures, and attain a reduction of these types of undesired events. Necci et al. (Necci et al., 2015) carried out a literature review to provide the state of the art on the assessment of domino effects responsible for High-Impact Low-Probability (HILP) events in the process industry. The outcome of this study made possible the quantitative assessment of domino scenarios in risk analysis and safety management. Raviv et al. (Raviv et al., 2017) investigated near-misses and accidents related to cranes in the construction industry and evaluated their severity level through the Analytic Hierarchy Process (AHP). In 2017, Bakar et al. (Bakar et al., 2017) analyzed 770 major accidents in the chemical industry collected from the American CSB, the European eMARS, the Japanese FKD, and the French ARIA databases; they focused on failures associated with process safety management and aimed at identifying the most common accident contributors. Recently, Nakhal et al. (Nakhal et al., 2021b) investigated the occupational and operational industrial safety data collected in the Major Hazard Incident Data Service database (MHIDAS) through Business Intelligence (BI) tools and Machine Learning (ML) algorithms.

It is worth mentioning that most of the accidents databases include hydrogen-related undesired events, even if they are not built to collect accidents specifically related to hydrogen technologies. Nevertheless, the presence of these events has enabled the publication of several reports specific to hydrogen management. For instance, the report "Accidentology involving hydrogen" (ARIA, 2009) is based on several hydrogen-induced accidents reported in the ARIA database. Moreover, in 2007, RISCAD published a detailed accident progress flow for an explosion at a High-compressed Hydrogen Energy Generator (HHEG) (Wada et al., 2007), while in 2012, eMARS dedicated a lesson learned bulletin to six accidents involving hydrogen (European Commission, 2012). However, the first structured database for hydrogen-related undesired events was developed by Kreiser et al. in 1994 and reported 287 incidents, but it has never been available to the public and was interrupted (Wen et al., 2022).

At present, there are two main public databases specific for hydrogen-related events. The European Hydrogen Incidents and Accidents Database (HIAD 2.0) and the HydrogenTools Lessons Learned (H_2TOOLS) (PNNL, 2022), developed by the Pacific Northwest National Laboratories and financed by the U.S. Department of Energy. These databases collect many common events and have the primary objective to provide an extensive and publicly available accidents database dedicated to hydrogen-related applications in order to better understand the risks associated with hydrogen production, handling, and storage. On the one hand, H_2TOOLS aims to provide a fine selection of lessons learned from previous events involving hydrogen with specific information and quantitative details (Weiner and Fassbender, 2012). On the other, HIAD 2.0 has less restrictive inclusion criteria and it seems more prone to accommodate larger-scale statistical evaluations (Wen et al., 2022). The main features of the most important safety databases are summarized in Table 1, along with the number of hydrogen-related undesired events reported. Databases no more updated or unavailable in English have been excluded since unsuitable for the aims of this study.

Thanks to these incident databases, it became possible to learn about the root causes of past undesired events. For instance, in 2011, Mirza et al. (Mirza et al., 2011) analyzed 32 hydrogen processing incidents collected in the Hydrogen Incident Reporting Database (HIRD) to identify weak points, optimize processes, and facilitate risk assessment.

Table 1
Characteristics of the most important safety databases.

Database	Hydrogen specific	N° of H_2-related events	Main features
ARIA	No	395	Publicly available online High quality event reports not always available in English Detailed narrative descriptions Unstructured quantitative information Detailed root cause analysis Lessons learned provided
eMARS	No	96	Publicly available online High quality event reports Events classified as "major accidents" by the Seveso Directive General qualitative description Structured and detailed quantitative information Lessons learned not provided
FACTS	No	481	Commercially available Quality of information depending on the primary sources Combination of structured fields and narrative descriptions Detailed consequence analysis Single root cause defined Lessons learned provided
H_2TOOLS	Yes	221	Publicly available online High quality event reports Detailed qualitative information Lacking and unstructured quantitative information Primary cause and contributing factors defined Lessons learned provided with high level of detail
HIAD 2.0	Yes	628	Publicly available upon request as an Excel spreadsheet Quality of information depending on the primary sources Multi-use platform to derive information for risk assessment Combination of structured fields and narrative descriptions "Main cause" defined neglecting the contributing factors Lessons learned provided depending on the primary sources

Statistical results about the effects, causes, and consequences have been provided. Finally, Sakamoto et al. (Sakamoto et al., 2016) used H_2TOOLS, HIAD, and the Japanese High-Pressure Gas Safety Act Database to analyze incidents in hydrogen refueling stations in Japan and the USA, and identify the associated safety issues. The authors highlighted that most leakages due to material damage and fracture are caused by design errors and underestimation of the fatigue deterioration rate.

To sum up, this overview of industrial accident databases demonstrates the importance of investigating previous events to learn from the past and avoid the reoccurrence of similar events in the future. Even if several databases for hydrogen-related incidents have been analyzed in the past, the analyses have always been limited to a small number of events, which were selected and investigated one by one to learn from their root causes. Otherwise, this study aims to gain knowledge from a systematic analysis of a large number of hydrogen-related undesired events to help industries to improve their safety management system, thus guaranteeing an increasingly widespread rollout of hydrogen technologies. The BA approach has been used to systematically and automatically mine information from the HIAD 2.0 database. This tool has the advantage to employ a structured data model, thus allowing the multi-variable and flexible analysis of a large dataset and a safety-informed decision-making process. In addition, it creates a dynamic interface which can be continuously improved with future updates of the source database to overcome the safety challenges associated with these emerging technologies.

3. Exploring HIAD 2.0

The study is grounded on data available in the Hydrogen Incidents and Accidents Database, a repository tool that includes reports of industrial accidents related to hydrogen and its derivatives. As stated in the “Introduction” section, HIAD was created by the European Commission Joint Research Center (JRC) within the framework of the Network of Excellence on Hydrogen Safety (HySafe) 2004 – 2009 (JRC, 2004). Since experts of JRC took care of maintaining and updating the database, new events were regularly provided to HIAD. These events were reviewed and validated by JRC experts, before becoming publicly available. The purpose of the HIAD database was to facilitate the exchange of lessons learned from hazardous events involving hydrogen to improve the information network and prevent similar unexpected events in the future (Kirchsteiger et al., 2007). In 2017, JRC together with Fuel Cell and Hydrogen 2 Joint Undertaking (FCH 2 JU) upgraded the HIAD database into HIAD 2.0 and integrated it as part of the activities of the European Hydrogen Safety Panel (EHSP) 2009 – 2022 (Melideo et al., 2019).

Reports in HIAD 2.0 database are intended for public use; hence, confidential information is not included in the database, and the focus is placed on reporting facts, avoiding blame apportioning. All data have a publicly available primary source. As far as possible, HIAD 2.0 provides a traceable link to the source of information (i.e., the French database ARIA, the European database eMARS, the British database IChemE, the Japanese database RISCAD, various American databases, scientific articles, newspapers, and industrial reports). The quality of the descriptions is completely dependent upon the information offered by the primary sources and their level of detail. Quality labels are provided and range from two, if the majority of quantitative descriptors are missing, to five, if lessons learned and root cause analyses are available with good technical details. This approach is based on the assumption that hazardous event reports from investigations can be a powerful tool in raising risk awareness and promoting safety management (Gyenes and Wood, 2016).

Regarding the information collected in HIAD 2.0, the database contains all the parameters necessary to know what happened and how the undesired event can be described in detail. HIAD 2.0 is currently (as for the 1st of January 2023) offline due to the renewal and maintenance of the last release of the HIAD database; works are ongoing to find a new online platform capable of allowing users to access the data and perform their searches. At present, all the collected records have been exported into an Excel workbook that allows users to access and analyze the data according to their needs (the Excel workbook used in this study is updated until the 1st of January 2022). The file contains six spreadsheets:

- **Events –** major classification, narrative summary, systems involved, date, location, and cause classification;
- **Facility –** description of the applications, storage conditions, location type, and pre-event conditions;
- **Consequences –** effects in terms of both human and property losses for the affected facilities;
- **Lessons Learnt –** corrective measures adopted;
- **Event Nature –** quantitative information on the emergency action, the characteristics of the release, the leak type, and the fire consequences;
- **Reference –** primary source of information.

There are some parameters allowing to gather the detailed information regarding each event among the spreadsheets: the Event ID (i.e., the registration number on the database), Quality Label (i.e., the information regarding the level of detail of the report), Event (i.e., the tag to describe the event), and Full Description (i.e., the descriptive summary of the incident, with detailed information). Table 2 summarizes the main parameters considered for each spreadsheet in HIAD 2.0.

It must be noted that not all these fields are consistently filled in, depending on the quantitative details provided by the primary source for each event. For instance, an event with Quality Label 2 has much less available information compared with an incident that is classified with Quality Label 5. Fig. 1 shows the distribution of quality of information regarding the undesired events reported in HIAD 2. For approximately 1.4% of the total events, a final assessment of the Quality Label is still missing. In addition, 48.7% have been classified as “Low quality” since most of the quantitative descriptors are not provided; for 28.7% of the total events the source of information is considered of “Good quality”. Moreover, 9.9% and 10.9% of the total events have “High quality” and “Very high quality” reports, in which root causes analyses and lessons learned are available, and quantitative technical details are provided.

Regarding the causes of the undesired events, the database defines for each report one of the following cause categories for the release:

- **Technical or mechanical causes –** The system was not designed taking into proper account the operating conditions (i.e., temperature and pressure) or hydrogen applications, there were a lack of ATEX components or a wrong selection of electric devices type;

Table 2
Structure of HIAD 2.0 spreadsheets and parameters.

Spreadsheet	Parameters
Events	Classification, Physical consequences, Application stage, System involved, Region, Country, Date, Cause, Cause commented
Facility	Application stage, Application chain, Application, Storage medium, Storage quantity, Actual pressure, Design pressure, Location type, Location description, Operational condition, Pre-event summary
Consequences	Total number of injured persons, Total number of fatalities, Environmental damage, Currency, Property loss (onsite and offsite), Post-event summary, Official legal action, Investigation comments
Lessons learnt	Lessons learnt
Event nature	Emergency action, Emergency evaluation, Release type, Release substance, Release consequences, Release duration, Release rate, Release amount, Release pressure, Hole shape, Hole length, Hole width, Hole diameter, Hole area, Ignition source, Ignition delay, Detonation, Deflagration, High-pressure explosion, High-voltage explosion, Flame type, Cloud surface, Cloud volume, Flame length, Flame surface, Flame volume, Heat radiation
References	Sources, Documents

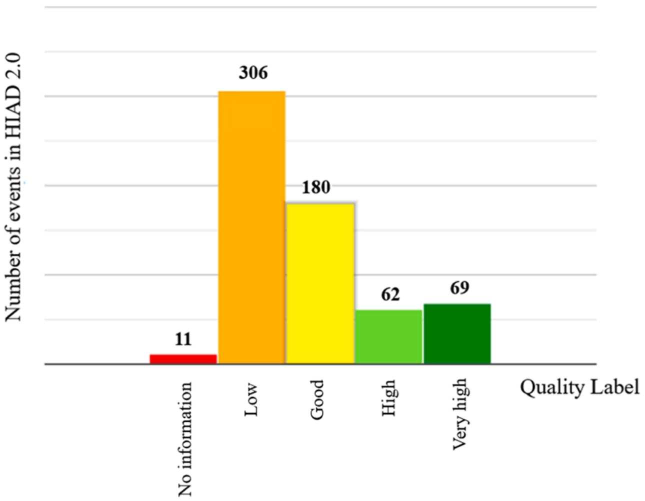


Fig. 1. Distribution of quality of information regarding the events reported in HIAD 2.0.

otherwise, even though the appropriate component was selected and installed, it failed due to material degradations or manufacturing errors undetected by inspection and monitoring activities;

- **Operational causes –** Although the component was selected according to the expected operating conditions, it failed due to improper installation and monitoring; such events might have occurred during normal operations or during maintenance or other special activities;
- **Organizational causes –** These incidents and accidents were originally caused by lacking safety barriers, failure to learn from previous events, lack of coordination and planning, and poor health and safety culture; most of these undesired events were related to outdated maintenance guidelines;
- **Human errors –** These events were caused by inadequate training and competence levels of the operators, tired, overstressed, or bored staff, individual medical problems, errors due to unpleasant working conditions or constant disturbances;
- **Environmental and external causes –** External fires, bolts, car accidents, etc.

3.1. Limitations and strengths of HIAD 2.0

HIAD 2.0 is designed as a multi-tasking communication platform. It can be suitable for deriving lessons learned from past events and has the potential to become a data source for Quantitative Risk Assessment (QRA). While most other databases have inclusion criteria based on the severity of the consequences, event records in HIAD 2.0 are not limited to real incidents and accidents, but also to hazardous situations which could have resulted in severe consequences. In addition, data collected are not limited to a short time span, as in the case of MHIDAS and IChemE, but cover a long period (from 1884 to 2021) and are continuously updated with new reports. By way of illustration, the number of validated events increased from 272 in 2018 to 628 in 2022, and this trend is expected to continue in the forthcoming years due to the increasing utilization of hydrogen as an energy carrier.

Nevertheless, HIAD 2.0 cannot become, at present, a tool for QRA due to the small number of events made available by the limited market penetration of hydrogen technologies. A total of 628 records is insufficient for deriving failure probabilities for components belonging to the hydrogen technology chain (Melideo et al., 2019; West et al., 2022). Hence, at present hydrogen-specific components use failure rates from different technologies (such as data from the oil and gas industry) for QRA. In addition, most event reports do not provide enough quantitative details for this type of analysis. Fig. 1 shows how many incidents and accidents collected in HIAD 2.0 have a low or medium quality information, and only 20.9% of the total events report detailed and quantitative information and provide root cause analysis and lessons learned.

On the other hand, the reliability and quality of the information in HIAD 2.0 is ensured by rigorous selection and validation processes. The European Hydrogen Safety Panel plays the role of the event provider, while JRC is a validator. Firstly, the EHSP members deliver to the JRC the description of the incidents using a template containing the same event descriptors used in the database. Then, the JRC experts assess the data and decide if the event descriptors have the minimum qualifications required to become a new entry in HIAD 2.0. This step often involves an improvement feedback loop with the event provider. Non-validated events remain in HIAD 2.0 but are not visible to users (Wen et al., 2022). This “four-eyes validation process” guarantees the quality of information. The “hidden” events are not included in this study since they can lead to unreliable statistics and meaningless results. If, on the one hand, this approach reduces the number of events available for the analysis, on the other hand, it eliminates the risk of troubling the waters with inaccurate information resulting from non-validated events.

As previously stated, HIAD 2.0 collects hydrogen-related undesired events that occurred worldwide; hence, it is important to be cautious before deriving general conclusions: the historical and geographic distribution of the accidents is biased by different regulatory frameworks. In addition, certain industrial sectors are bound to publicly report incidents, while others are not, and this leads to differences in the number and level of detail of the reports. Another important drawback is associated with the root causes of the events. The choice of a single cause category imposed by HIAD 2.0 is often a limitation. Most accidents are triggered by multiple causes, possibly hierarchically dependent. This drawback is partially overcome by using a narrative description of the triggering causes. However, the *ad-hoc* solution is incompatible with the need to provide quantitative statistics or reliable predictions through machine learning techniques.

4. Methodology

Business Analytics (BA) refers to the ability to use raw data to improve the business organization’s model. In addition, BA aims at identifying data sources, boosting the ability to manage information access, and handling the information flow within an appropriate architecture to assess business needs (Loshin, 2003). Therefore, BA process combines databases, analytical tools, architectures, applications, and methodologies (Chaudhuri et al., 2011) to transform raw data into information and facilitate the decision-making process and cost-benefit analysis. Moreover, it improves the quality and efficiency of the process output (Garg and Mhaskar, 2018).

On the other hand, Extraction – Transformation – Loading (ETL) process is used to obtain high-quality data from the deal of information provided by the database (Souibgui et al., 2019). This data requires treatment operations such as sorting, aggregation, cleaning, splitting, arranging, and others to foster data integration. An architecture data model needs to be developed to manage heterogeneous source formats, removing obsolete and overlapping data and continuously transforming the structure of the data source (Kimball and Caserta, 2004). An ETL process generally consists of six tasks (Trujillo and Luján-Mora, 2003):

1 **Selecting the sources** – this step allows the process to select the data, extract the information, and load the data into the software to be processed.
2 **Transforming the sources** – this step provides new data derived from the transformation tasks. Some of these tasks are filtering the data, converting them into codes, calculating values or metrics, changing formats, and/or surrogating key values. All the issues (e.g., duplicates, typing, formating, sorting errors, and missing data) are properly managed.

3. **Joining the sources** – all the sources or data processed must be joined to load all the data in a unique model.
4. **Selecting the target to load** – this step provides information regarding the target or targets to be loaded and selected. Therefore, this step establishes the information recipient.
5. **Mapping source attributes to target attributes** – the attributes or parameters extracted and transformed must be mapped to obtain the corresponding target.
6. **Loading the data** – the target is populated with the newly transformed data.

Fig. 2 shows how the ETL process is performed to extract the desired data and build the data model.

The data cleansing and treatment represent a crucial step of the ETL process. However, since data sources change over time, this process is not a one-time event, and the data model must be periodically updated. The data model integration with ETL requires four steps (Sharda et al., 2018):

1. **Identify end-user requirements** – what information do the analyst own? What further information are required? In this case, the answers refer to the accident reports collected in HIAD 2.0 and ought to be explored both at a specific and aggregate level.
2. **Identify the data source** – the data can be distributed among numerous locations. The HIAD 2.0 database was publicly available online and is currently provided upon request as an Excel file.
3. **Design the data model** – the research is intended to (i) create the data store through an analytic workspace; (ii) generate the summary data and store them in the analytic workspace objects as the base-level data through queries; (iii) prepare the data for access and grant access to end-users. The HIAD 2.0 data model consists of 18 queries and is reported in Fig. 3 in the “Results” section.
4. **Create and distribute reports** – following the data model development, a set of descriptive analyses is proposed in dedicated reports for the benefit of the end-users.

Microsoft Power BI is the software tool used for this analysis; it is an interactive and dynamic data visualization interface with a primary focus on business intelligence. The model developed has high potential since it allows the analysis of all the parameters in HIAD 2.0. In this work, the focus is placed on the temporal and spatial distribution of the incidents, the field of application in which the event occurred, the causes and the effects in terms of human losses, as well as the type of release (i.e., liquid, gas, or mixed phase in confined, semi-confined, or open space). The visualization of these information is provided in the section dedicated to the results.

5. Results

The data model architecture, which is the basis for the analysis of the HIAD 2.0 database, has been realized using the Crow’s Foot notation and is represented in Fig. 3. Therefore, the data collected in HIAD 2.0 have been used to perform descriptive analyses regarding hydrogen-related undesired events in the past decades. The information collected in HIAD 2.0 has not been modified or changed. Furthermore, the results are consistent with the selection of EHSP and the validation of JRC. The classification of event types, facilities, and consequences complies with the existing standards and codes for hydrogen safety, such as the European Scale of Industrial Accidents (ISO, 2015).

As shown, in the “Events”, “Events nature”, “Facility”, and “Consequences” queries, all the parameters share a one-to-one relationship (red line in Fig. 3). This relationship implies that each record in one query corresponds to only one other record in another query and vice-versa. In addition, the parameter “Event ID” represents the primary key to link the queries. On the other hand, the data model presents many-to-one relationships in the parameters “Event cause”, “Event nature flame”, “Event nature hole”, “Event nature - release substance”, “Event system involved”, “Event cause comments”, “References”, “Lesson learnt”, “Quality classes”, “Consequence post event summary”, “Facility pre event summary”, “Facility application”, and “Facility location description” (blue line in Fig. 3). These relationships define that for multiple records in one table, there is only one record in another query. In addition, the model has one-to-many relationships (green line in Fig. 3) in the branches. These relationships, in which one record in one table could have multiple corresponding records in another query, are the opposite of the many-to-one. In this case, the primary keys are “Country list” and “Application stage”. The primary keys are the parameters that link the query to build the model. In other words, they represent a set of parameters whose values uniquely identify a row in the query. Therefore, the relational database is designed to enforce the uniqueness of primary keys by allowing only one row with a given primary key value in a query. The data model highlights the large number of interactions needed to relate and manage the information. All the statistics and the results analyzed in the following derive from this data model.

The data model has been designed to provide a group of visuals, tables, and graphs in a set of dashboards that allow a continual tracking of important metrics. These dashboards allow a visual-descriptive analysis of the safety data reported in HIAD 2.0. By way of illustration, Fig. 4 proposes an excerpt from one dashboard of the report. The features of the dashboard can be listed as follows:

- A slider visual that allows filtering the records by year.

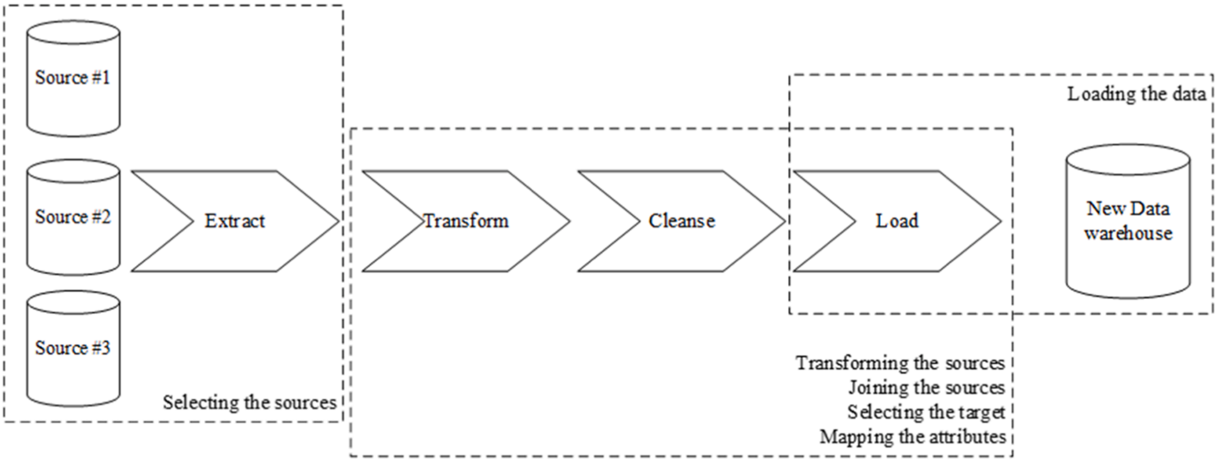


Fig. 2. Extraction – Transformation – Loading process diagram representation.

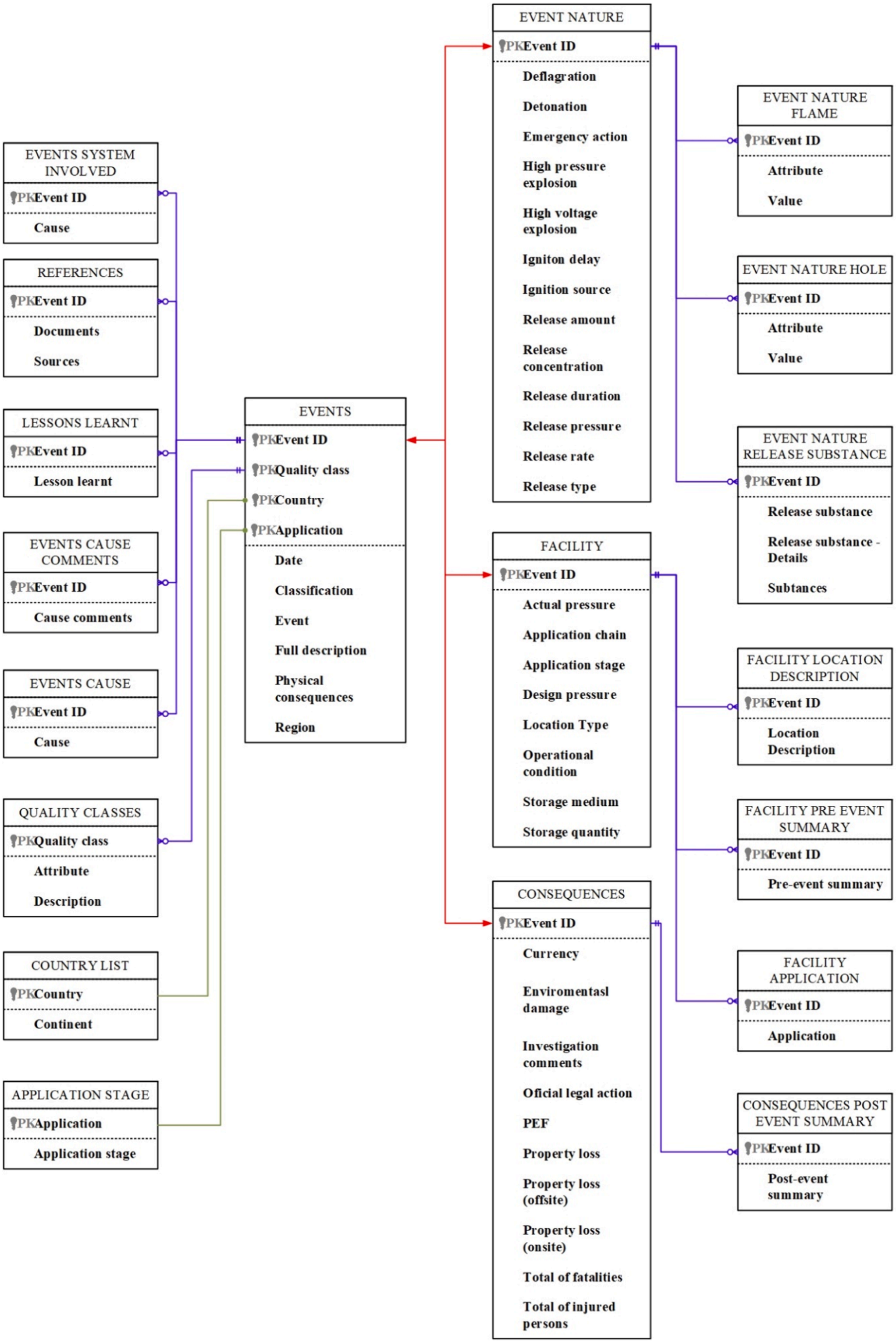
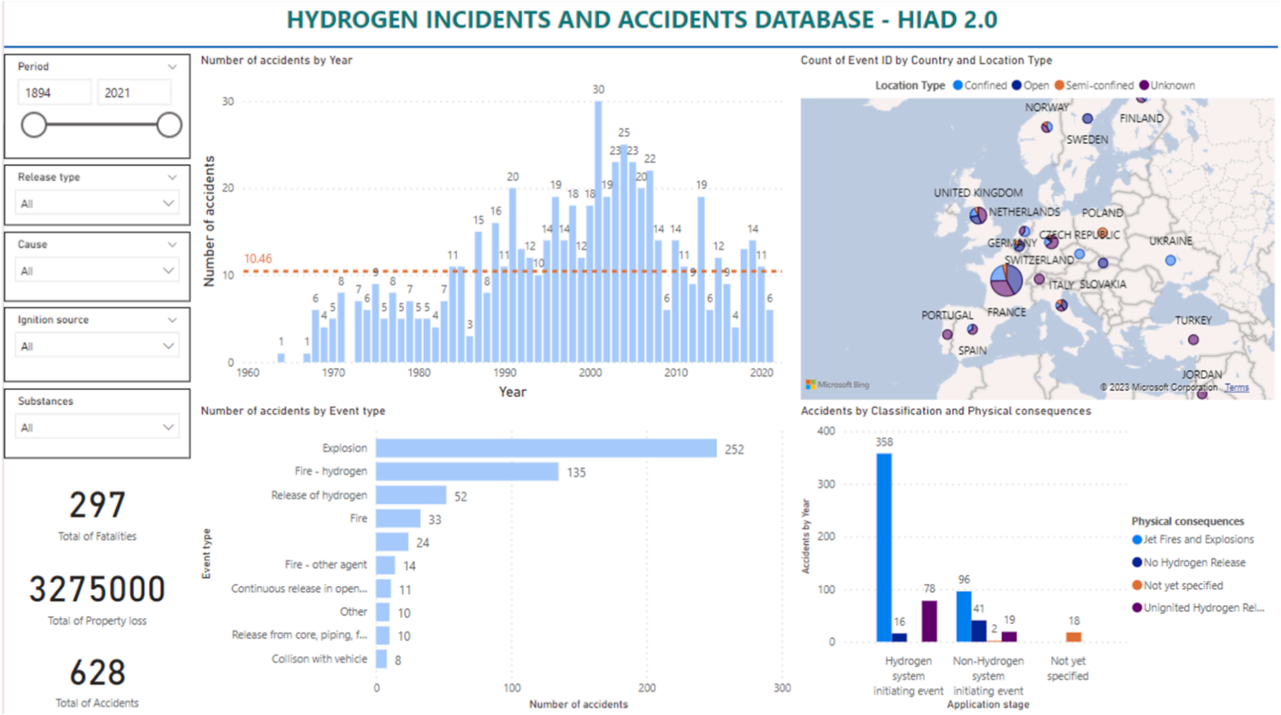


Fig. 3. HIAD 2.0 data model, where the parameters sharing one-to-one, many-to-one, and one-to-many relationships are linked by red lines, blue lines, and green lines, respectively (PK = Primary Key).

- Four filters, i.e., release type, ignition source, causes, and substances, which make it possible to select one or more desired parameters to force the dashboard to update the information and show the data associated with those parameters.
- Three visuals showing the total number of fatalities, the amount of property loss (in US dollars), and the total number of accidents.
- Two clustered column charts which report the number of accidents collected in the database per year, and the number of accidents by application stage, divided by the physical consequences of the accidents.
- A geographical map that shows the distribution of the accidents per country.



HYDROGEN INCIDENTS AND ACCIDENTS DATABASE - HIAD 2.0

Period: 1894 – 2021

Release type: All

Cause: All

Ignition source: All

Substances: All

297 Total of Fatalities

3275000 Total of Property loss

628 Total of Accidents

Fig. 4. An excerpt dashboard designed to summarize the information reported in HIAD 2.0.

- A stacked bar chart which reports the number of accidents by event type, industrial application, and location description.

Any dashboard of the report has been created dynamically, allowing drill-through and cross-data functionalities. These functionalities allow exploring in the same environment data from multiple pages and automatically restricted by the active filters.

At present, the database collects 628 accidents that occurred worldwide between 1890 and 2021. The undesired events in 2022 and 2023 are not included since they have not been validated by the panel of JRC experts. Nevertheless, the model can be automatically upgraded with additional information, by simply updating the HIAD 2.0 source database with new event records. In this perspective, a dynamic approach for identifying the hazards, evaluating risk, providing statistics, and suggesting preventive strategies is crucial, considering the relatively little operational experience with hydrogen-specific technologies. This process can be continuously adapted and improved thanks to the return of experience from past accidents, thus facilitating risk-informed decision-making by industrial operators and safety experts.

Fig. 5 is a clustered column chart that presents the annual occurrence of incidents recorded in the period 1960 – 2020. A total of 626 accidents occurred in this period, while only two events are recorded before 1964, i.e., the Berlin-Tempelhof accident in 1884, in which 400 hydrogen gas cylinders exploded in a military airfield (event ID534 in HIAD 2.0), and the iconic incident of the Zeppelin LZ 129 Hindenburg in 1937 (event ID10 in HIAD 2.0).

In addition, the geographical distribution of the events is shown in Fig. 6 to complement the temporal analysis. The worldwide distribution is represented on the left, while on the right the focus is placed on European countries. The size of the bubbles is directly related to the total number of events that occurred in each country, while the colors indicate the type of release (i.e., confined, semi-confined, in open space, and unknown).

The focus has been placed on European countries since most reported

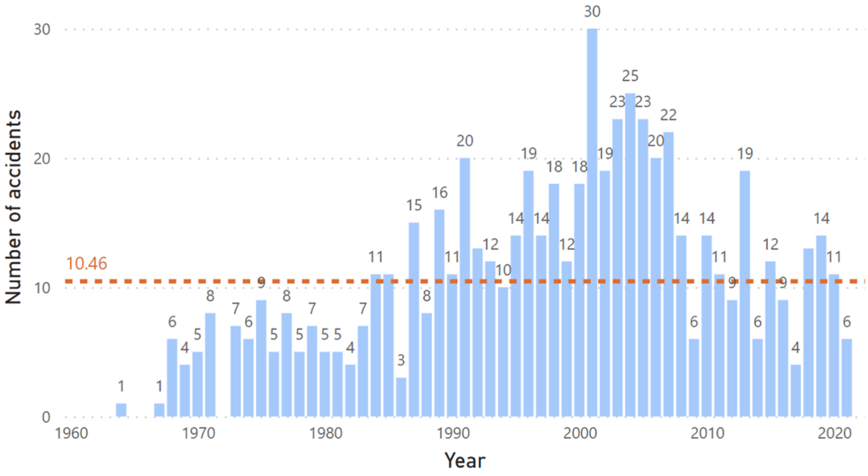


Fig. 5. HIAD 2.0 accidents reports collected over time.

Fig. 6. Worldwide distribution of events by location type and number of accidents (light blue = confined release; orange = semi-confined release; blue = release in open space; purple = unknown).

events occurred in Europe: more than 50% of the total incidents in HIAD 2.0 are concentrated in a comparatively small geographical area. The countries with the highest number of events are France, the USA, the UK, Germany, Canada, Italy, Japan, Finland, and Norway. It is worth mentioning that 86 reports (13.7%) do not specify the region nor the country in which the accident occurred. This analysis has been complemented by Table 3, in which the first ten countries by number of accidents are ranked, and the events are classified by release type.

The "Unknown" release type has the highest contribution among the incidents; the USA and France have the greatest number of incidents in which the location type is classified as "Unknown", with 78 and 55 events, respectively. Moreover, there are several releases in "Open space" (141 events, representing 22.5% of the total). France and the USA have the highest number of releases that occurred outdoor, i.e., 64 and 33 events, respectively. Finally, the releases in confined and semi-confined spaces account for 20.5% of the total events, but they are prevalent in Germany, Japan, Finland, and Norway.

Table 4 summarizes the consequences of hydrogen-related undesired events in terms of number of fatalities (333) and injured persons (1162) and sorts them by continent.

According to HIAD data, Europe is the continent where hydrogen-related undesired events are most frequent; these 357 releases resulted in 91 fatalities and 451 injuries, corresponding to 0.25 casualties and 1.26 injured persons per event on average. On the other hand, America, the continent which ranks second in terms of events recorded (i.e., 170), has 132 fatalities and 547 injured persons. In addition, 86 releases occurred in Asia, with 94 casualties and 152 injured persons. Finally, only four undesired events occurred in Africa; despite their small number, they are responsible for seven casualties and nine injured persons.

Table 4
Fatalities and injured persons reported in HIAD 2.0 by continents.

Continent	Number of events	Fatalities	Fatalities per event	Injured persons	Injuries per event
Africa	4	7	1.75	9	2.25
America	170	132	0.78	547	3.22
Asia	86	94	1.09	152	1.77
Europe	357	91	0.25	451	1.26
Not reported	11	9	0.82	3	0.27
Total	628	333	0.53	1162	1.85

Table 5 presents the distribution of the undesired events by field of application, specifying the number of deceased and injured persons for each application category:

Most undesired events were recorded in the chemical and petrochemical industry (338 events) and resulted in 222 fatalities and 658 injured persons; 69 releases occurred in hydrogen transportation and distribution and resulted in nine casualties and 126 injuries, while 35 events with 16 fatalities and 72 injured persons occurred in hydrogen production. Road vehicles and non-road vehicles are responsible for 24

Table 3
Accident distribution by release type per country.

Country	Release type				Total
	Confined	Open space	Semi-confined	Unknown	
France	37	64	7	55	163
USA	25	33	5	78	141
Not reported	8	12	2	64	86
UK	10	14	4	32	61
Germany	6	4	3	19	32
Canada	2	5	1	10	18
Italy	2	5	2	3	12
Japan	3	2	1	6	12
Finland	6	2	0	3	11
Norway	3	0	1	3	7
Total	102	141	26	273	542
	16.2%	22.5%	4.1%	43.5%	86.3%

Table 5
Fatalities and injured persons sorted by application stage and ordered by number of accidents.

Application stage	Events	Fatalities	Injured persons
Chemical and Petrochemical Industry	338	222	658
Other	113	26	178
Hydrogen Transportation and Distribution	69	9	126
Hydrogen Production	35	16	72
Road Vehicles	24	1	4
Not Reported	13	15	96
Laboratory and R&D	13	0	23
Non-Road Vehicles	9	8	7
Hydrogen Refueling Stations	8	0	0
Commercial Use	6	0	1

Table 6

Accidents, ordered by number and classified by cause type with focus on fatalities and injured persons.

Cause type	Number of events	Percentage of events	Fatalities	Fatalities per event	Injured persons	Injuries per event
Technical / Mechanical	145	23.1%	39	0.27	144	0.99
Unknown	126	20,0%	73	0.58	150	1.19
Operational	121	19.2%	59	0.49	228	1.88
Human Error	59	9.4%	20	0.34	145	1.54
Organizational	57	9.0%	53	0.93	311	5.87
Environmental / External	10	1.6%	15	1.5	91	9.10
Other Causes	18	2.8%	7	0.39	16	0.89
Total	533	85.1%	266		1085	

and nine events, respectively; non-road vehicles caused eight fatalities and seven injuries, while road vehicles one and four, respectively. Incidents in laboratories and in hydrogen refueling stations did not result in casualties. Finally, 113 events, that resulted in 26 fatalities and 178 injured persons, are classified as “Other” application category, proving the variety of industrial fields in which hydrogen and hydrogen-containing compounds are used.

A total of 533 reports are defined by cause type, while a clear and unique cause is not defined for the remaining 95 events. In some cases, it may be difficult to identify clear root causes and chains of events, such as in presence of multiple domino effects. In addition, expert analyses are not publicly available in the case of legal aspects involved in the investigation. Table 6 summarizes the classification of these events by cause category, specifying the number of events and the consequences in terms of human casualties and injured persons.

Technical and mechanical causes account for almost a quarter of the total. Despite their high frequency, undesired events triggered by technical causes seem to have often resulted in relatively minor consequences since they are responsible for 39 fatalities and 144 injuries, i.e., 0.27 fatalities and 0.99 injured persons per event on average. The operational causes related to improper installation and monitoring of hydrogen equipment are responsible for 121 incidents. Errors during normal operations or maintenance activities represent the primary cause of death with 59 fatalities and 228 injured persons. Moreover, the releases due to lack of safety barriers, coordination, improper inspection planning, and poor safety culture (i.e., organizational causes) account for 9.0% of the total. Nevertheless, they are the second cause of death and the primary cause of injuries with their impressive 0.93 fatalities and 5.87 injured persons per event on average. The failures traceable to human errors are 59, namely 9.4% of the total. These events resulted in 20 fatalities and 148 injured persons. In addition, only five events were caused by environmental and external causes, but they are responsible for 15 fatalities and 91 injuries, making them the most serious accidents in terms of human losses. Finally, 126 events (i.e., 20.0% of the total) have unknown causes. These events are highly lethal since they caused 73 fatalities and 150 injured persons.

Fig. 7 depicts the distribution of the release phase (gas, liquid, mixed, or other) and puts it in relation with the release type (in open space, confined, or semi-confined).

From HIAD 2.0, 260 accidents have been related to gaseous releases. Among these 260 events, 94 occurred outdoor (15.0%), 53 in confined (8.4%), and 20 in semi-confined spaces (3.2%); in addition, 95 gaseous hydrogen releases are classified as “Unknown” (15.1%). A total of 22 events involved liquid substances; 12 of these are liquid releases outdoor, while two events occurred indoor. Moreover, 15 accidents in HIAD 2.0 are classified as “Mixed” release type. Among them, six events occurred outdoor, four in confined, and one in semi-confined spaces.

6. Hydrogen-induced material failures: lessons learned

Hydrogen-induced Damages (HDs) of metals are long-known phenomena in material science. They are defined as environmentally assisted degradations that result from the synergistic action of hydrogen exposure and uptake into the materials, a susceptible microstructure, and the presence of stresses, residual or applied. HDs often manifest themselves as a reduction in the mechanical properties of components that can result in catastrophic failures (Burt, 2015). The main parameters inherent to the three aforementioned factors can be roughly summarized as follows (Barnoush and Vehoff, 2010):

1 **Environment** – temperature, pressure, hydrogen amount, form, purity, and source;
2 **Field type** – load and stress fields, fatigue, electrochemical driving force;
3 **Material** – chemical composition, microstructure, surface treatments, thermal treatments, and presence of material inhomogeneities (e.g., welds).

Several degradation mechanisms may arise in applications where hydrogen is not directly employed but is generated from the dissociation of hydrogen-containing compounds, such as H_2S, HF, and HCl (American Petroleum Institute, 2020). Nevertheless, these damages can lead to equipment failure, eventually resulting in near-catastrophic consequences and significant human and material losses.

Over the years, 70 registered undesired events have been triggered by material failures of equipment directly or indirectly exposed to hydrogen. The majority of these were caused by corrosion-related degrading mechanisms, such as galvanic corrosion (e.g., the event ID16 in HIAD 2.0), atmospheric corrosion (e.g., events ID83, ID341, ID527, and others), external corrosion (e.g., events ID952 and ID958) sulfuric acid corrosion (e.g., events ID93, ID95, ID114, and others), hydrofluoric and hydrochloric acid corrosion (e.g., events ID488, ID634, and ID864), corrosion under insulation (e.g., ID796 and ID807), and corrosion fatigue (e.g., ID122, ID131, ID261, and others). Some others were triggered by mechanical and thermal fatigue (e.g., events ID208, ID772, and ID981). For these accidents, degradations inherent to hydrogen-metal interaction can be considered a contributing factor which facilitated the component’s failure, even if could not be considered its primary cause. On the other hand, hydrogen-induced damages were the triggering mechanisms of 24 undesired events collected in HIAD 2.0. These accidents are summarized in Table 7. Each accident report is identified through its event ID and its date. In addition, information about the damage mechanism responsible for the material failure, the components affected and their material, the presence of welds or heat-affected zones (HAZs), and the chemicals involved is provided.

Hydrogen Embrittlement (HE) is a well-known hydrogen-induced damage, and it is responsible for 14 of the 24 events collected in Table 7. It is a form of degradation by which ductility, fracture toughness, fatigue performance, and sometimes strength of susceptible materials may be significantly reduced due to the uptake of atomic hydrogen into the material bulk (Brocks Hagen and Alvaro, 2020; Esaklul, 2017). Hydrogen-Induced Cracking (HIC) can be considered a form of hydrogen embrittlement characterized by the brittle fracture of an alloy that was expected to be ductile. The inherent dangerousness of failures related to HE is the lack of premonitory signs which makes the failure prediction very challenging. As shown in Table 7, high-pressure storage vessels, cylinders, hydrogen pipes in chemical plants, and pipelines for hydrogen transport are the components most relevant when it comes to safety and

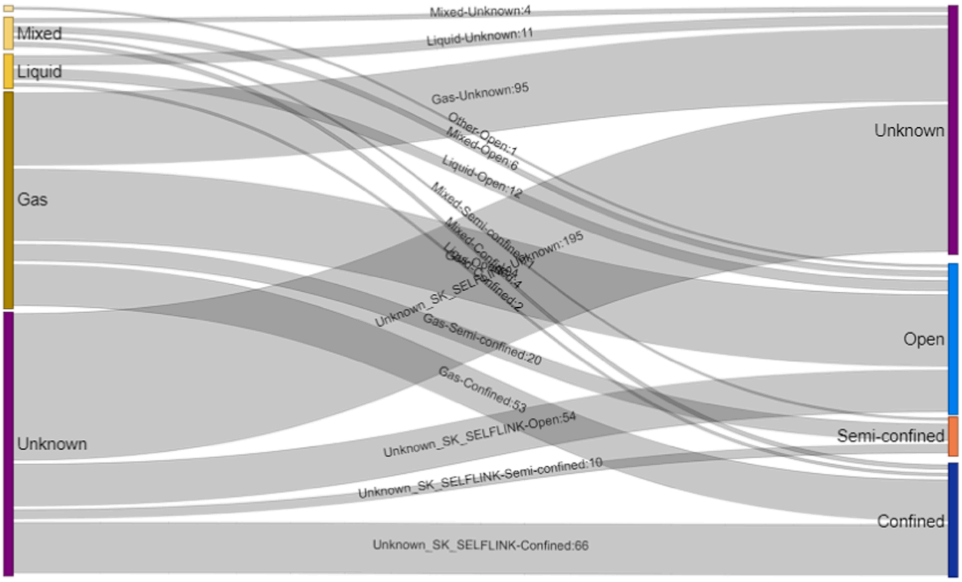


Fig. 7. Release phase classification explained by release type in which accident occurred.

material compatibility with respect to HE (Laureys et al., 2022). In addition, cryogenic tanks and hydrogenation reactors can be eventually affected by this type of material damage. Weldments are often the most critical part of a given component: 57.1% of the failures due to hydrogen embrittlement occurred in the proximity of welded joints. This is because welding processes produce the most critical combination of the whole component in terms of susceptible microstructure, i.e., the HAZs and the highest local stress (both residual stresses and applied ones). Based on the findings in Table 7, low-alloy ferritic steels, extensively used for cylindrical hydrogen vessels, high-strength steels, for transportation pipelines, 400 series stainless steels, and some high-strength nickel-based alloys can suffer hydrogen embrittlement. Several events, such as the Berlin-Tempelhof accident in 1894 (event ID534), led to improvements in standards and regulations regarding hydrogen compatibility with the metallic materials of the containment systems. Moreover, the accident that occurred on the 1st of August 1982 (event ID775) proves that operating conditions such as high pressure, temperature slightly higher than room temperature, and relatively high hydrogen purity, can enhance the HE effects. In addition, the lack of post-weld heat treatments (PWHT), together with the lack of knowledge about the microstructure of the heat-affected zone, has triggered events ID637 and ID775. Furthermore, the undesired event that occurred on the 1st of October 1988 (event ID898) demonstrated that equipment which was not originally designed for hydrogen service can be extremely susceptible to HE and this can introduce additional risks.

Another important HD which resulted in six undesired events is the High-Temperature Hydrogen Attack (HTHA). It is a form of decarburization which occurs in components exposed to hydrogen at high temperature and pressure for a long time (American Petroleum Institute, 2020). The surface decarburization of the steel is normally not detrimental to the point of limiting the life of equipment but tends to reduce the component strength. On the other hand, if internal HTHA occurs, CH_4 is formed internally and cannot diffuse through the steel; the pressure build-up of the gaseous methane may trigger blisters, fissures, and intergranular cracks that can lead to equipment failure (Campari et al., 2022a). As shown in Table 7, hydrotreaters in desulfurization units for refining hydrocarbons and steam methane reformers for hydrogen production have operating conditions under which HTHA can occur if they are not made of suitable materials. Damage can occur randomly in the base metal or welds and HAZs (Khoshnaw and Gubner, 2021). Half of the failures due to HTHA and hydrogen blistering occurred in the proximity of weldments. Carbon steels are particularly susceptible to this kind of damage, but also steels with high content of molybdenum may be affected by HTHA. The event that occurred on the 14th of November 1974 (event ID620) led to important improvements in the standards for material compatibility for hot and cold hydrogen service. Moreover, the accident of the 2nd of April 2010 (event ID883) resulted in improvements in the recommended practice API 581 for risk-based inspection of equipment damaged by HTHA.

The Hydrogen-Induced Stress Corrosion Cracking (HISCC) can be considered a transition from the typical hydrogen embrittlement and stress corrosion cracking (Woodtli and Kieselbach, 2000). When a component is expected to work in a corrosive environment, it is often cathodically protected. A side effect of improper cathodic protection is the production and uptake of atomic hydrogen in the protected metal, and the subsequent local embrittlement of welds that are not subjected to post-weld heat treatments. Normally, a consistent part of the atomic hydrogen should recombine at the metal surface to form gaseous hydrogen which is not able to penetrate through the metal lattice. However, once hydrogen atoms are available in the material bulk, they diffuse and accumulate throughout the material based on concentration and stress gradients, and they accumulate to energetically favorable sites in material inhomogeneities (i.e., grain and phase boundaries, precipitates, carbides, etc.). Table 7 shows how high-pressure cylinders and compressors may be affected by HISCC when they operate with corrosive fluids and are made of susceptible materials, such as high-strength low-alloy steels, carbon steels, and brass. Table 8 summarizes the most effective techniques to detect and monitor the occurrence of hydrogen damages in equipment exposed to hydrogen.

Lessons learned from the analysis of accidents seems to indicate that most of these undesired events could have been prevented through timely and effective inspection and maintenance activities. Lack of updated inspection plans, low inspection frequency, and insufficient detail in inspection activities often resulted in severe accidents with significant economic losses and sometimes injured persons and casualties. Table 9 highlights the root causes of these hydrogen-induced material failures, the inspection and maintenance activities implemented in practice, and the optimal strategies that should have been carried out to prevent the incidents. These preventive strategies are directly retrieved from the “Lessons learned” spreadsheet in HIAD 2.0 or from the original accident reports (whenever available). Thus, they have been validated by the JRC experts. While any replacement action is described in detail, the specific methodologies for non-destructive inspections are rarely reported in the database; hence, they have been

Table 7
Incident reports in HIAD 2.0 related to hydrogen-induced material failures of industrial equipment.

Event ID	Date	Damage Mechanism	Material	Component	Failure in the weld	Substances released
ID26	10/03/1978	Hydrogen-induced stress corrosion cracking	Steel	High-pressure vessel	Yes	$H_2 + CH_4$
ID101	07/06/1996	Hydrogen-induced cracking	Austenitic steel CrNiMnW	Cryogenic tank	Yes	$C_2H_6 + C_2H_4 + CH_4 + H_2$
ID107	01/06/2005	Hydrogen blistering	0.5% Mo steel	Refinery	Yes	–
ID117	28/07/2005	High-temperature hydrogen attack	Carbon steel	Residual hydrotreater unit	No	H_2
ID194	14/09/2000	Hydrogen-induced cracking	Steel	Pipe in ammonia plant	No	$NH_3 + H_2 + N_2$
ID196	14/07/2000	Hydrogen embrittlement	Steel	Pipe in ammonia plant	Yes	$NH_3 + H_2$
ID241	01/05/1998	Hydrogen-induced stress corrosion cracking	Brass	High-pressure cylinders	No	H_2
ID351	03/03/2000	Hydrogen-induced stress corrosion cracking	Steel	Hydrogen compressor	No	H_2 + Hydrocarbons
ID384	16/01/2008	Hydrogen-induced cracking	Alloy Inconel 600	High-pressure cylinders	No	H_2
ID385	04/05/2012	Hydrogen embrittlement	440c stainless steel	Hydrogen tank	No	H_2
ID534	25/05/1894	Hydrogen embrittlement	Steel	High-pressure cylinders	No	H_2
ID567	06/07/1996	Hydrogen embrittlement	Steel	High-pressure vessel	Yes	Hydrocarbons + H_2
ID615	21/12/1975	Hydrogen embrittlement	Steel	High-pressure vessel	No	H_2
ID620	14/11/1974	High-temperature hydrogen attack	Steel	Catalytic reformer	No	H_2 + Hydrocarbons
ID637	17/05/1984	NS	Steel	Desulfurization unit	Yes	H_2 + Hydrocarbons
ID648	02/02/1973	Hydrogen embrittlement	Steel	Octafiner reactor	Yes	H_2
ID675	01/06/1993	Hydrogen-induced stress corrosion cracking	Steel	Hydrogen compressor	No	$H_2 + H_2S$
ID775	01/08/1982	Hydrogen embrittlement	Austenitic stainless steel	Pipe in ammonia plant	Yes	H_2 + Syngas
ID863	09/12/1984	High-temperature hydrogen attack	Steel	High-pressure syngas pipe	Yes	$H_2 + NH_3$
ID883	02/04/2010	High-temperature hydrogen attack	Carbon steel	Catalytic reformer and naphtha hydrotreater unit	No	Naphtha + H_2
ID893	04/06/2019	Hydrogen embrittlement	Steel	Hydrogen pipe in refinery	Yes	H_2
ID898	01/10/1988	Hydrogen embrittlement	Steel	Hydrogen tank	No	H_2
ID902	13/12/1984	Hydrogen embrittlement	Steel	Desulfurization unit	Yes	Oil + H_2
ID926	18/09/2014	Hydrogen embrittlement	Steel	Starch hydrogenation reactor	Yes	Starch + H_2

Chemical formulae: CH_4, Methane; C_2H_6, Ethane; C_2H_4, Ethylene; H_2, Hydrogen; H_2S, Hydrogen Sulfide; N_2, Nitrogen; NH_3, Ammonia.

suggested accordingly with the recommended practice API RP 571 (American Petroleum Institute, 2020), depending on the damage mechanism responsible for the equipment failure.

The identification and the analysis of the root cause of these accidents allowed for improving the existing standards and codes for hydrogen-materials compatibility. For instance, the Technical Report ISO/TR 15916 (ISO, 2015) provides a list of materials and their suitability for hydrogen applications, indicates design measures to minimize local residual stresses (e.g., PWHT) and avoid cold plastic deformations. In addition, the “Technical Reference for Hydrogen Compatibility of Materials” (San Marchi and Somerday, 2012) provides a substantial amount of experimental data on hydrogen effects on metallic materials. The codes and practices produced by EIGA on material testing and selection (EIGA, 2014, 2011, 2006) divide materials for hydrogen service into several classes based on chemical composition and strength. In addition, ISO 11114–4:2017 (ISO, 2017) prescribes the test methods for selecting steels resistant to HE under monotonic stress (i.e., not suitable for components subjected to cyclic loading), while ANSI/CSA CHMC1–2014 (ANSI, 2014) provides a method to compare the performances of components operating in compressed hydrogen environments. The most recent standards and codes for material testing and selection for hydrogen service have certainly improved the design of new hydrogen-specific components. Nevertheless, it is important to remember that most hydrogen equipment currently in operation has been designed before the publication of these standards and codes. Hence, pipelines, tanks, and instrumentation for hydrogen handling and storage may be not compliant with these guidelines or are recycled from other applications (e.g., event ID898). In this perspective, rigorous methodologies for inspection planning are required to minimize the arbitrariness in carrying out safety audits. The risk-based inspection policy is the most beneficial guideline to perform inspection and maintenance of industrial facilities. Despite this, it failed several times in preventing the occurrence of hydrogen-induced material failures, because these damages are not properly addressed by the existing RBI standards and recommended practices (Campari et al., 2022a). This underestimation of the probability of failure of equipment exposed to hydrogen environments led to several accidents (e.g., ID194, ID196, ID351, ID615, and others). Moreover, some recent events have priors

Table 8

Inspection and monitoring techniques useful to detect and size the hydrogen damages (American Petroleum Institute, 2020).

Hydrogen damage	Inspection technique	Characteristics
HE	Liquid penetrant testing (PT)	Only for surface cracking inspection
	Magnetic particle testing (MT)	Only for surface cracking inspection
	Wet fluorescent particle testing (WFPT)	Only for surface cracking inspection
	Shear wear ultrasonic testing (SWUT)	Can detect and size cracks
	Phased array ultrasonic testing (PAUT)	Can detect and size cracks
HTHA	Visual testing	Can detect only superficial blisters
	Automatic ultrasonic backscatter testing (AUBT)	Can detect microvoids and microfissures, not very reliable
	Angle beam spectral analysis (ABSA)	Can detect microvoids and microfissures, not very reliable
	Field metallographic replication (FMR)	Only for examination of areas known to be damaged
	Time of flight diffraction (TOFD)	Can detect surface and internal damages
	Phased array ultrasonic testing (PAUT)	Can detect surface and internal damages
HISCC	Liquid penetrant testing (PT)	Can detect surface-breaking cracks
	Magnetic particle testing (MT)	Can detect surface-breaking cracks
	Wet fluorescent magnetic particle testing (WFMT)	Can detect surface-breaking cracks
	Shear wear ultrasonic testing (SWUT)	Can determine the depth of cracks
	Phased array ultrasonic testing (PAUT)	Can determine the depth of cracks

with similar causes, thus proving the inability to learn from the past. This is the case of events ID902 and ID926, which occurred in 1984 and 2014, respectively, and were both caused by undetected hydrogen-enhanced fatigue in a HAZ. In addition, events ID863 and 883, dating back to 1984 and 2010, can be both attributed to undetected blistering on the inner surface of the component.

7. Discussion

Hydrogen is widely used in industry for refining hydrocarbons, treating metals, producing fertilizers, and processing foods. Refineries use hydrogen to lower the sulfur content of fuels, and its demand has constantly increased as sulfur-content regulations have become stricter due to a greater environmental awareness worldwide (Speight, 2020). Historically, hydrogen has been mostly used as a chemical for several processes in various industrial fields rather than as an energy carrier, and this trend remains true nowadays. The time distribution of the events collected in the HIAD 2.0 database is plotted in Fig. 5. Most of the accidents occurred in the period from 1990 to 2020, while the number of events recorded in the previous decades is considerably lower. The year with the highest number of incidents is 2001, with 30 reported events. An almost negligible number of accidents is reported in the 1960s. Regarding the utilization of hydrogen as an energy carrier, in the 1970s, a wave of interest came forward due to the oil crisis and the lack of fossil sources resulting from the Yom Kippur War. The second peak of application of hydrogen technologies tried to face the increasing concerns on climate change at the beginning of the 1990s (Scita et al., 2020) and resulted in important research projects for hydrogen production and utilization in Europe, Japan, and the USA (IRENA, 2022). The third wave of interest began in the 2000s with the growing unease regarding the oil price and the environmental impact of the transport sector (Scita et al., 2020). This technological hype is reflected by the allocation of

Table 9

Causes of hydrogen-induced material failures, inspection activities implemented, and optimal preventive strategies.

Event ID	Event cause	Inspection/ maintenance carried out	Optimal preventive strategies
ID26	Absence of PWHT; severe operating environment	Not relevant	Proper PWHT; PT, MT, or WFMT on welds and HAZs
ID101	Different microstructure (martensite) in the HAZ	Insufficient maintenance	Maintenance required before the start-up
ID107	Undetected blistering due to HTHA; improper material selection	Not implemented	Visual inspection; component replacement with 1.25 Cr steel
ID117	Rapid HTHA degradation; carbon steel component accidentally switched with low-alloy steel component during maintenance activities	Improper maintenance	Post-reassembly testing after maintenance (Preventive Maintenance Inspection); higher training of the operators
ID194	Undetected crack in a pipe of a heat exchanger	Not implemented	SWUT or PAUT along the entire pipe
ID196	Undetected crack in a weldment	Not implemented	SWUT or PAUT on welds and HAZs
ID241	Design shortcomings in high-pressure cylinder; improper material selection	Not relevant	Component replacement
ID351	Undetected HISCC of a hydrogen compressor; assembly error after maintenance	Improper maintenance	SWUT or PAUT on piston rod; higher training of the operators
ID384	Undetected HIC of a rupture disk; improper material selection	Leak detection	SWUT or PAUT on rupture disk made of high-strength Ni alloy
ID385	Use of generic equipment for hydrogen service; improper material selection	Not relevant	Component replacement with 316 stainless steel; adoption of active and passive safety barriers; modification of normal plant operations
ID534	Improper material selection; lack of codes to calculate the remaining lifetime of components	Not implemented	PT on the cylinder surface; component replacement
ID567	Off-design operating conditions (high pressure, near-ambient temperature) fostering HE	Improper inspection	PT on the inner surface of the vessel; SWUT or PAUT on welds and HAZs
ID615	Undetected crack in a storage tank	Not implemented	PT, MT, or PAUT on the vessel surface
ID620	Improper material selection; undetected HTHA on several components	Not implemented	Frequent FMR, TOFD, or PAUT on the inner surface of the catalytic reformer
ID637	Insufficient PWHT	Not relevant	Proper PWHT; PT, MT, or WFMT on welds and HAZs
ID648	Undetected HE on HAZ; insufficient PWHT	Not implemented	SWUT or PAUT on welds and HAZs; proper PWHT
ID675	Improper material selection	Not relevant	Component replacement
ID775	Insufficient PWHT; different microstructure in the HAZ	Six improper repairs in four years	Frequent SWUT or PAUT on welds and HAZs, particularly in the bends of the pipe
ID863		Not implemented	TOFD or PAUT on the inner surface of the

(continued on next page)

Table 9 (*continued*)

Event ID	Event cause	Inspection/ maintenance carried out	Optimal preventive strategies
	Undetected blistering on the inner surface of the pipe due to HTHA		pipe; component replacement
ID883	Undetected blistering on the inner surface of the catalytic reformer due to HTHA	Improper inspection	TOFD or PAUT on the inner surface of the pipe; component replacement
ID893	Undetected HE under insulation	Ex-post thickness measurements and radiographic checks	SWUT or PAUT
ID898	Recycling of a cylinder; severe operating conditions (high H_2 purity, high pressure, ambient temperature, high stress level)	Inspection performed but not documented	PT, MT, or PAUT on the surface; analysis of the component's history
ID902	Undetected hydrogen-enhanced fatigue crack growth on HAZ	Not implemented	SWUT or PAUT on welds and HAZs
ID926	Undetected hydrogen-enhanced fatigue crack growth on HAZ	Not implemented	SWUT or PAUT on welds and HAZs

fundings for pilot projects on hydrogen technologies to which corresponded an increased number of hydrogen-related incidents (IEA, 2019). The reduction of incidents in the 2010s can be attributed to the improvement in operational safety in the chemical and petrochemical industries. It is worth mentioning that the historical accident distribution is affected by a significant loss of information due to underreporting, especially in past decades. Moreover, the validation process required to update the database with a new event can take months up to several years. For these reasons, the information collected by HIAD 2.0 cannot be used to draw any definitive conclusions and is always affected by a certain degree of uncertainty. In the next few years, another increase in hydrogen-related accidents may occur in connection with the widespread rollout of hydrogen technologies in novel technological fields, such as the automotive applications (including passenger cars, public transport, and heavy-duty vehicles), maritime and aeronautic sectors (European Commission, 2022; Ustolin et al., 2022).

Fig. 6 shows the geographical distribution of the undesired events. It results that more than a half of the events occurred in Europe, one quarter in North America, and one seventh in Asia and Australia. The accidents in other regions account only for 2.4% of the total. One of the main reasons for this difference can be related to the source of information used to update HIAD 2.0. In fact, more than 40% of the accidents collected come from the French ARIA, the British IChemE, and the European eMARS databases. On the other hand, only 6% derives from the Japanese RISCAD database and another 6% from various American safety reporting systems. As a result, France is the country with the highest number of accidents, followed by the United States, the United Kingdom, Germany, Canada, Italy, Japan, Finland, and Norway, while there are limited sources for past events in Asia, Africa, South America, and Oceania. Another reasonable cause of this uneven distribution of hydrogen-related incidents around the world is related to the different magnitude of the adoption of hydrogen technologies in various countries. Historically, the vast majority of investments in hydrogen-based fuels have been made in Europe, North America, and Japan (IEA, 2019). This trend is expected to change in the forthcoming years, with the advance of China at the forefront of research in this technological field (Xie and Freeman, 2019) and with the expected development of a global energy trade involving new countries able to produce renewable hydrogen at most competitive costs. Hence, it is important to point out that the geographical distribution cannot be considered indicative of the actual worldwide distribution of hydrogen-related industrial accidents.

Different considerations can be made regarding the geographical distribution of fatalities and injuries. Table 4 shows how America is the continent with the highest number of fatalities and injured persons due to hydrogen-related industrial incidents. Europe and Asia follow, even if significant differences are noticeable: while it is reported that a massive number of undesired events occurred in Europe, they often resulted in minor consequences; on the other hand, even if much fewer incidents are reported in Asia, they caused a higher number of deceases and a relatively small number of injured persons. Finally, the database reports only four events in Africa, which caused a significant number of deceases and injuries. These differences across continents might be related to the dissimilar regulations on industrial incident reporting. In compliance with the Seveso III Directive (European Parliament, 2012), in Europe, the national authorities are obliged to report all industrial accidents involving dangerous substances to the European Commission and provide all the information required to develop root cause analyses and safety investigations. In the USA, the Emergency Planning and Community Right-to-Know Act (EPCRA), also known as Title III of the Superfund Amendments and Reauthorization Act (SARA) (US EPA, 2012), is a pioneering framework for chemical accidents which include risk communication and public information disclosure provisions. On the other hand, the Japanese Pollutant Release and Transfer Register (PRTR) law does not require industries to report and publicly share hazardous chemical inventories; the PRTR only dictates that, in the case of hazardous chemical releases, businesses are obligated to evaluate the volume of substance released and report it to the local authorities. Hence, Japan seems to lag behind the EU and the US in terms of regulations regarding accident reporting (Tzioutzios et al., 2022). No information is available regarding the regulatory framework in Africa, but it is reasonable to assume the most nations do not have specific requirements for minor incidents reporting. This could justify the limited number of accidents reported by the database and their relatively high severity in terms of injuries and fatalities. In general, in countries with laxer regulations regarding accident reporting, the operators have a lower propensity to notify minor incidents to the competent authorities. In fact, undesired events could cost an organization much more than just the cost of repair in terms of loss of image and reputation.

Table 5 summarizes the distribution of undesired events by type of application. The chemical and petrochemical industries have the largest share of hydrogen-related incidents. This is reasonable since the chemical and process industries together with refineries and petrochemical plants have been historically the biggest consumers of hydrogen, and they still retain this primacy (Ausfelder and Bazzanella, 2016). The stricter regulations regarding fuel quality and the ever-lower oil quality are expected to increase the hydrogen demand in the oil and gas industry. Considering the hydrogen supply chain, from production to final usage, the most critical stages are transportation and distribution. In fact, transporting hydrogen is a challenging undertaking due to its extreme chemical properties and its tendency to permeate, degrade, and embrittle most metallic materials (Campari et al., 2022a; Ustolin et al., 2021). Hydrogen leaks and spills are difficult to detect and can easily result in serious consequences due to the large flammability range, the low ignition energy, and the high burning velocity of this substance (Aursand et al., 2020; Kotchourko and Jordan, 2022; Ustolin et al., 2020c, 2020a; van Wingerden et al., 2022). Hydrogen production, mainly by methane-steam reforming, is also prone to several incidents, often related to the high-temperature and relatively high-pressure in a reforming reactor (i.e., 800 – 900 °C and 30 bar) (Speight, 2020). Hydrogen-fueled road vehicles and non-road vehicles account for 33 events together. It is worth mentioning that these car accidents have a very low lethality, and they are often non-hydrogen system initiating events (i.e., they are normal car accidents involving one or more hydrogen-powered vehicles and are not caused by a malfunctioning or a failure of the fuel cell powertrain). Finally, incidents that occurred in laboratories, refueling stations, or commercial facilities did not cause any fatalities and only a small number of injured persons.

Table 6 summarizes the distribution of the events classified by cause.

Technical and mechanical errors represent the main cause with a share of 23.1%, even if they have limited consequences in terms of casualties and injured persons. They comprehend both materials-related and design-related causes. The formers include the non-ideal selection of materials for hydrogen applications and the activation of material degradation mechanisms like corrosion and fatigue, while the latter is the adoption of insufficient safety systems and the lack of precautions during the design stage. Operational causes (accounting for 19.2% of the total) are related to installation errors and improper inspection and maintenance activities. Examples of operational causes are the lack of updated inspection plans, an insufficient inspection frequency, the lack of inspection tailored toward hydrogen-induced degrading mechanisms, and the lack of indications about the lifetime of components. Although these events represent a lower share than technical and mechanical failures, they have a two-fold lethality impact. Human errors turn out to be responsible for 9.4% of the total reported events. Even if a certain number of human errors is unavoidable, it can be lowered through sufficient training of the technical personnel. While applications of hydrogen in the chemical and process industries are well-known and there is already relevant expertise in this field, applications of hydrogen as an energy carrier are still relatively novel. Hence, first responders are less expert in the accident scenarios they may face, and they may not be prepared to respond correctly and promptly (Wen et al., 2022). In addition, small human errors may result in more serious events with severe consequences. Organizational causes (accounting for 9.0% of the total) are related to safety systems management factors and most of these failures are due to outdated or inappropriate maintenance guidelines. These undesired events have often serious consequences in terms of both casualties and injured persons. Nevertheless, most of these accidents could be avoided through effective inspection and maintenance activities. Preventive maintenance is crucial to guarantee the continuity of production and avoid undesired releases of hazardous substances in the environment (Campari et al., 2022a). In this perspective, the risk-based inspection (RBI) methodology is widely considered the most beneficial guideline for inspection planning (Mohamed et al., 2018). This approach assumes that high-risk components account for a small portion of the entire plant. The inspection plan ranks the equipment on a risk basis and prioritizes the inspection and maintenance of high-risk components, dedicating a reduced maintenance effort for low-risk ones (American Petroleum Institute, 2019, American Petroleum Institute, 2016). Finally, environmental and external causes are responsible for a limited number of events, but they have the highest lethality (the only ten reported accidents caused 15 fatalities and 91 injuries). Unfortunately, it is very difficult to intervene in these types of events. The comprehensive lesson learned is that accidents might be triggered by several causal events, which might be insignificant if taken individually, but could cause severe consequences when they occur simultaneously (Wen et al., 2022).

After the loss of containment due to leakages or cracks, hydrogen can be released as a gas, liquid, or mixed phase depending on its type of storage. Fig. 7 shows that most of the accidents reported in HIAD 2.0 are related to gaseous releases, while liquid and mixed releases account only for fewer instances. This fact is expectable since hydrogen has been historically used in gaseous form in most of its applications. Around 31% of the hydrogen produced worldwide was used in gaseous form in refineries, 63% in the chemical industry, and around 6% in other kinds of applications. On the other hand, less than 1% of the total share of hydrogen was used in liquid form, particularly for rocket propulsion, automotive, and specific industrial applications (such as the semiconductor industry) (Ausfelder and Bazzanella, 2016). The main advantage of liquid hydrogen lies in its higher energy density on a volume basis, which facilitates its transportation through thermally insulated tanks capable of storing LH_2 at cryogenic temperature (around -253 °C) and near-ambient pressure (Campari et al., 2022b). For this reason, most liquid hydrogen releases occurred during transportation through truck trailers or cargo trains, or in aerospace applications. Another noteworthy aspect is the classification by release type (i.e., in confined, semi-confined, or open space). As shown in Fig. 7, most hydrogen-related accidents occurred outdoor, while a comparatively smaller number of events took place in confined or semi-confined spaces. It is well-known that an accidental hydrogen release indoor can easily result in explosions and has often serious consequences compared with a similar outdoor release (Tretsiakova-McNally and Makarov, 2022). Storing hydrogen outdoor (whenever possible) is generally considered a good safety measure to reduce the risk of explosions and high overpressures. The concern for hydrogen releases in confined and semi-confined locations and the necessity to better understand these events is proven by several European research projects, such as InsHyde ("Hydrogen releases in confined and partially confined spaces") (Venetsanos et al., 2011) and HyTunnel ("Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces") (European Union, 2019).

A final consideration should be made regarding the methodology adopted in this study. The development of the data model supported by BA tools can significantly facilitate the management of large datasets. On the one hand, the implementation of BA in the hydrogen safety field may assist the regulatory institutions in arranging new safety guidelines following a data-driven approach. On the other hand, these results are the preliminary stage towards more advanced information technology applications for safety management, which could indicate a way forward an increasingly safe utilization of hydrogen technologies.

8. Conclusion

This study presents a systematic analysis of the 628 undesired events reported in the publicly available HIAD 2.0 database. A BA approach has been used to mine information reported in the database and visualize statistical results regarding the incidents that occurred in different industrial sectors, countries, and location types. This application shows the potential for their future adoption for safety data management and process system technology. Safety and risk prevention often involve a large set of variables mutually interconnected which affect the functioning of the industrial facility. In this context, BA can support a multivariable analysis based on a structured data model. The research created a dynamic interface capable of facilitating a flexible analysis, providing answers, or even stimulating further questions, and allowing a safety-informed decision-making process. Although the case study is based on the undesired events in HIAD 2.0 database, this approach is highly significant also for other incident reporting systems. This methodology should be combined with machine learning clustering techniques, depending on future enhancements and updates of the HIAD 2.0 database, in order to improve safety management systems for hydrogen technologies (Nakhal et al., 2022; Qin and Chiang, 2019). This could increase the resilience of industrial equipment, facilitating and stimulating a worldwide utilization of hydrogen as a clean and sustainable energy carrier.

A total of 24 hydrogen-induced industrial failures caused by the utilization of materials incompatible with hydrogen were investigated in depth. The damage mechanisms responsible for the occurrence of accidental events were highlighted. The results of the analysis show how hydrogen embrittlement, in its various forms, caused a non-negligible number of failures. High-temperature hydrogen attack and corrosion due to acidic hydrogen-containing compounds (e.g., H_2S, HCl, and HF) may also be responsible for loss of containment and subsequent undesired releases of hazardous substances. According to the lessons learned, it is proven that a vast majority of these events could have been prevented through proper inspection activities. Regular audits against corrosion and adequate attention to potentially critical points, such as welds and joints, could have helped to detect any defect promptly to ensure timely maintenance. Regarding hydrogen embrittlement, some incidents were traced back to the lack of tailored inspection plans and lack of clear indications about the lifetime of components operating in a hydrogen environment. In fact, an effective methodology for planning preventive safety measures for hydrogen technologies is still unavailable.

These findings underline the necessity of a multidisciplinary approach to face the safety issues related to hydrogen-induced material failures of industrial equipment. It is necessary to strengthen the collaboration between two research fields that have been traditionally separated: materials science and RAMS (i.e., reliability, availability, maintainability, and safety) engineering. In addition, the current best practices, standards, and regulations on inspection and maintenance planning are not suitable for hydrogen technologies, since they do not consider most HDs, including hydrogen embrittlement. The RBI methodology could be a highly beneficial approach for planning inspections of hydrogen technologies. Hence, the next version of the RBI standards and recommended practices should consider HE as a potential material degradation to adopt this methodology for the emerging hydrogen infrastructure.

CRediT authorship contribution statement

Alessandro Campari: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Antonio Javier Nakhal Akel:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Federico Ustolin:** Supervision, Writing – original draft, Writing – review & editing. **Antonio Alvaro:** Supervision, Writing – review & editing. **Alessandro Ledda:** Funding acquisition, Writing – review & editing. **Patrizia Agnello:** Funding acquisition, Writing – review & editing. **Pietro Moretto:** Data curation. **Riccardo Patriarca:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Nicola Paltrinieri:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgments

This work was undertaken as a part of the research projects “Sustainability development and cost-reduction of hybrid renewable energies powered hydrogen stations by risk-based multidisciplinary approaches” (SUSHy) and “Safe hydrogen fuel handling and use for efficient implementation 2″ (SH$_2$IFT 2); the authors would like to acknowledge the financial support of the European Interest Group within the program EIG CONCERT-Japan (Grant No. 334340) and the Research Council of Norway (Grant No. 327009). The work of one author (A. Nakhal) is partly funded by INAIL (Italian National Institute for Insurance against Accidents at Work) – Department of Technological Innovations and Safety of Plants, Products and Anthropic Settlements, as part of the project “Resilience analysis for the evolution of industrial sociotechnical systems in critical or highly complex contexts”. The authors kindly acknowledge the European Commission Joint Research Center for providing the information collected in HIAD 2.0. The continuous update and improvement of HIAD 2.0 is financially supported by the European public-private partnership “Clean Hydrogen Joint Undertaking”.

References

Abohamzeh, E., Salehi, F., Sheikholeslami, M., Abbassi, R., Khan, F., 2021. Review of hydrogen safety during storage, transmission, and applications processes. J. Loss Prev. Process Ind. 72 https://doi.org/10.1016/j.jlp.2021.104569.

American Petroleum Institute, 2020. API RP 571 - Damage mechanisms affecting fixed equipment in the refining industry.

American Petroleum Institute, 2016. API RP 580 - Risk-based inspection.

ANSI, 2014. ANSI/CSA CHMC 1-2014 - Test methods for evaluating material compatibility in compressed hydrogen applications - Metals.

ARIA, 2009. Accidentology involving hydrogen.

American Petroleum Institute, 2019. API RP 581 - Risk-based inspection methodology.

Aursand, E., Odsæter, L.H., Skarsvåg, H., Reigstad, G., Ustolin, F., Paltrinieri, N., 2020. Risk and consequences of rapid phase transition for liquid hydrogen. In: 30th Eur. Saf. Reliab. Conf. ESREL 2020 15th Probabilistic Saf. Assess. Manag. Conf. PSAM 2020 1899–1906. https://doi.org/10.3850/978-981-14-8593-0.

Ausfelder, F., Bazzanella, A., 2016. Hydrogen in the chemical industry. Hydrogen Science and Engineering: Materials, Processes, Systems and Technology, pp. 19–39. https://doi.org/10.1002/9783527674268.ch02.

Autorité de Securité Nucleare, 2022. ASN Database [WWW Document]. URL https://www.asn.fr/ (accessed 7.14.22).

Bakar, H.T.A., Siong, P.H., Yan, C.K., Kidam, K., Ali, M.W., Hassim, M.H., Kamarden, H., 2017. Analysis of main accident contributor according to process safety management elements failure. Chem. Eng. Trans. 56, 991–996. https://doi.org/10.3303/CET1756166.

Barnoush, A., Vehoff, H., 2010. Recent developments in the study of hydrogen embrittlement: hydrogen effect on dislocation nucleation. Acta Mater. 58, 5274–5285. https://doi.org/10.1016/j.actamat.2010.05.057.

Bell, J., Healey, N., 2006. The causes of major hazard incidents and how to improve risk control and health and safety management: a review of the existing literature. HSL/2006/117.

Benson, R., Ild, C.T.S., Box, P.O., Personal, I., 1989. Process systems engineering : past, present a personal 13, 1193–1198.

Brocks Hagen, A., Alvaro, A., 2020. Hydrogen influence on mechanical properties in pipeline steel: state of the art.

Burt, V., 2015. Corrosion in the Petrochemical Industry, 2nd ed. ASM International, Materials Park, Ohio.

Campari, A., Darabi, M.A., Ustolin, F., Alvaro, A., Paltrinieri, N., 2022a. Applicability of risk-based inspection methodology to hydrogen technologies: a critical review of the existing standards. In: Proceedings of the 32nd European Safety and Reliability Conference (ESREL2022). https://doi.org/10.3850/978-981-18-5183-4_R13-01-095-cd.

Campari, A., Pio, G., Ustolin, F., Paltrinieri, N., Salzano, E., 2022b. Design and optimization of an emergency auto-thermal burner for liquid hydrogen. Chem. Eng. Trans. 91, 325–330. https://doi.org/10.3303/CET2291055.

Capelli-Schellpfeffer, M., Floyd, H.L., Eastwood, K., Liggett, D.P., 1998. How we can better learn from electrical accidents. In: IEEE Industry Applications Society 45th Annual Petroleum and Chemical Industry Conference (Cat. No.98CH36234), pp. 311–318. https://doi.org/10.1109/PCICON.1998.727996.

Carol, S., Vilchez, J.A., Casal, J., 2000. Updating the economic cost of large-scale industrial accidents: application to the historical analysis of accidents. J. Loss Prev. Process Ind. 13, 49–55. https://doi.org/10.1016/S0950-4230(99)00053-4.

Centre for Research on the Epidemiology of Disasters, 2022. ADIC Database [WWW Document]. URL https://www.adrc.asia/adrc/ (accessed 7.14.22).

Charvet, C., Chambon, J.L., Corenwinder, F., Taveau, J., 2011. Learning from the application of nuclear probabilistic safety assessment to the chemical industry. J. Loss Prev. Process Ind. 24, 242–248. https://doi.org/10.1016/j.jlp.2010.09.007.

Chaudhuri, S., Dayal, U., Narasayya, V., 2011. An overview of business intelligence technology. Commun. ACM 54, 88–98. https://doi.org/10.1145/1978542.1978562.

Christou, M., Konstantinidou, M., 2012. Safety of offshore oil and gas operations: lessons from past accident analysis, Ensuring EU hydrocarbon supply through better control of major hazards EUR 25646 EN. JRC Scientific Policy Rep.

das Chagas Moura, M., Lins, I.D., Droguett, E.L., Soares, R.F., Pascual, R., 2015. A multi-objective genetic algorithm for determining efficient risk-based inspection programs. Reliab. Eng. Syst. Saf. 133, 253–265. https://doi.org/10.1016/j.ress.2014.09.018.

DNV, 2012. World Offshore Accident Databank (WOAD) [WWW Document].

EIGA, 2014. Hydrogen pipeline systems IGC Doc 121/14.

EIGA, 2011. Hydrogen cylinders and transport vessels IGC Doc 100/11E.

EIGA, 2006. Gaseous hydrogen stations IGC Doc 15/06.

Esaklul, K.A., 2017. Hydrogen damage, in: trends in oil and gas corrosion research and technologies: production and transmission. Elsevier Inc. 315–340. https://doi.org/10.1016/B978-0-08-101105-8.00013-9.

European Commission, 2022. REPowerEU Plan [WWW Document]. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483 (accessed 9.14.22).

European Commission, 2020. eMARS Database [WWW Document]. URL https://emars.jrc.ec.europa.eu/en/emars/Content/(accessed 7.14.22).

European Commission, 2018. In-depth analysis in support of the Commission Communication COM(2018) 773 A Clean Planet for all, COM(2018) 773.

European Commission, 2012. Lessons learned bulletin No. 1 chemical accident prevention & preparedness issue on accidents involving hydrogen.

European Commission Joint Research Center, 2004. HySafe - safety of hydrogen as an energy carrier [WWW Document]. URL http://www.hysafe.org/ (accessed 7.12.22).

European Parliament, 2012. Seveso III Directive. Off. J. Eur. Union 1–37.

Garg, A., Mhaskar, P., 2018. Utilizing big data for batch process modeling and control. Comput. Chem. Eng. 119, 228–236. https://doi.org/10.1016/j.compchemeng.2018.09.013.

Geitner, F.K., Bloch, H.P., 2012. The Failure Analysis and Troubleshooting System - Practical Machinery Management for Process Plants, Fourth Edi. ed, Machinery Failure Analysis and Troubleshooting. Elsevier. https://doi.org/10.1016/b978-0-12-386045-3.00001-5.

Gyenes, Z., Wood, M.H., 2016. Lessons learned from major accidents relating to ageing of chemical plants. Chem. Eng. Trans. 48, 733–738. https://doi.org/10.3303/CET1648123.

He, G., Zhang, L., Lu, Y., Mol, A.P.J., 2011. Managing major chemical accidents in China: towards effective risk information. J. Hazard. Mater. 187, 171–181. https://doi.org/10.1016/j.jhazmat.2011.01.017.

European Union, 2019. HyTunnel-CS - Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces Document]. [https://hytunnel.net/ (accessed 8.12.22)].

Institution of Chemical Engineers, 2022. IChemE Database [WWW Document]. URL https://www.icheme.org/knowledge/safety-centre/resources/accident-data/(accessed 7.14.22).

International Energy Agency, 2021. Global Hydrogen Review 2021.

International Energy Agency, 2021. Net zero by 2050 - a roadmap for the global energy sector.

International Energy Agency, 2019. The future of hydrogen - Seizing today's opportunities.

IRENA, 2022. Geopolitics of the Energy Transformation: the Hydrogen Factor. IEA Publications.

ISO, 2017. ISO 11114-4 Transportable gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 4: test methods for selecting steels resistant to hydrogen embrittlement.

ISO, 2015. ISO/TR 15916 - Basic considerations for the safety of hydrogen systems.

Japanese Institute for Advanced Industrial Science and Technology, 2022. RISCAD Database [WWW Document]. URL https://sanpo.aist-riss.jp/riscad/ (accessed 7.14.22).

Keren, N., West, H.H., Rogers, W.J., Gupta, J.P., Mannan, M.S., 2003. Use of failure rate databases and process safety performance measurements to improve process safety. J. Hazard. Mater. 104, 75–93. https://doi.org/10.1016/S0304-3894(03)00236-X.

Khan, F., Hashemi, S.J., Paltrinieri, N., Amyotte, P., Cozzani, V., Reniers, G., 2016. Dynamic risk management: a contemporary approach to process safety management. Curr. Opin. Chem. Eng. 14, 9–17. https://doi.org/10.1016/j.coche.2016.07.006.

Khare, A., Vishwakarma, M., Parashar, V., 2017. A review on failures of industrial components due to hydrogen embrittlement & techniques for damage prevention. Int. J. Appl. Eng. 12, 1784–1792.

Khoshnaw, F., Gubner, R., 2021. Corrosion atlas case studies: hydrogen damage, First ed.

Kidam, K., Hurme, M., 2013. Analysis of equipment failures as contributors to chemical process accidents. Process Saf. Environ. Prot. 91, 61–78. https://doi.org/10.1016/j.psep.2012.02.001.

Kimball, R., Caserta, J., 2004. The Data Warehouse ETL Toolkit - Practical Techniques for Extracting, Cleaning, Conforming, and Delivering Data. Woodhead Publishing Ltd, Indianapolis, USA.

Kirchsteiger, C., 2001. How frequent are major industrial accidents in Europe? Process Saf. Environ. Prot. Trans. Inst. Chem. Eng. Part B 79, 206–210. https://doi.org/10.1205/095758201750362244.

Kirchsteiger, C., Vetere Arellano, A.L., Funnemark, E., 2007. Towards establishing an International Hydrogen Incidents and Accidents Database (HIAD). J. Loss Prev. Process Ind. 20, 98–107. https://doi.org/10.1016/j.jlp.2006.10.004.

Kotchourko, A., Jordan, T., 2022. Hydrogen Safety for Energy Applications - Engineering Design, Risk Assessment, and Codes and Standards, Hydrogen Safety For Energy Applications. Butterworth-Heinemann, Oxford. https://doi.org/10.1016/c2018-0-00342-4.

Laureys, A., Depraetere, R., Cauwels, M., Depover, T., Hertelé, S., Verbeken, K., 2022. Use of existing steel pipeline infrastructure for gaseous hydrogen storage and transport: a review of factors affecting hydrogen induced degradation. J. Nat. Gas Sci. Eng. 101 https://doi.org/10.1016/j.jngse.2022.104534.

Leoni, L., De Carlo, F., Paltrinieri, N., Sgarbossa, F., BahooToroody, A., 2021. On risk-based maintenance: a comprehensive review of three approaches to track the impact of consequence modelling for predicting maintenance actions. J. Loss Prev. Process Ind. 72 https://doi.org/10.1016/j.jlp.2021.104555.

Loshin, D., 2003. Business intelligence.ß: the Savvy Manager's guide, getting onboard with emerging IT. San Francisco, USA.

Melideo, D., Moretto, P., Wen, J., 2019. HIAD 2.0 - hydrogen incidents and accidents database. In: Proceedings of the International Conference on Hydrogen Safety ICHS.

Mirza, N.R., Degenkolbe, S., Witt, W., 2011. Analysis of hydrogen incidents to support risk assessment. Int. J. Hydrogen Energy 36, 12068–12077. https://doi.org/10.1016/j.ijhydene.2011.06.080.

Mohamed, R., Che Hassan, C.R., Hamid, M.D., 2018. Implementing risk-based inspection approach: is it beneficial for pressure equipment in Malaysia industries? Process Saf. Prog. 37, 194–204. https://doi.org/10.1002/prs.11903.

Nakhal, A.J.A., Hovstad, J.S., Ruth, M.S., Parmeggiani, S., Patriarca, R., Paltrinieri, N., 2022. A machine learning approach to analyze natural hazards accidents scenarios. Chem. Eng. Trans. 91, 397–402. https://doi.org/10.3303/CET2291067.

Nakhal, A.J.A., Patriarca, R., Di Gravio, G., Antonioni, G., Paltrinieri, N., 2021a. Business intelligence for the analysis of industrial accidents based on MHIDAS database. Chem. Eng. Trans. 86, 229–234. https://doi.org/10.3303/CET2186039.

Nakhal, A.J.A., Patriarca, R., Di Gravio, G., Antonioni, G., Paltrinieri, N., 2021b. Investigating occupational and operational industrial safety data through Business Intelligence and Machine Learning. J. Loss Prev. Process Ind. 73, 1–17. https://doi.org/10.1016/j.jlp.2021.104608.

Necci, A., Cozzani, V., Spadoni, G., Khan, F., 2015. Assessment of domino effect: state of the art and research Needs. Reliab. Eng. Syst. Saf. 143, 3–18. https://doi.org/10.1016/j.ress.2015.05.017.

Nuclear Reactor Commission, 2022. NRC Database [WWW Document]. URL https://www.nrc.gov/reactors.html (accessed 7.14.22).

Pacific Northwest National Laboratory, 2022. H2TOOLS Lessons learned [WWW Document]. URL https://h2tools.org/lessons?search_api_fulltext= (accessed 7.14.22).

Paltrinieri, N., Dechy, N., Salzano, E., Wardman, M., Cozzani, V., 2012. Lessons learned from toulouse and buncefield disasters: from risk analysis failures to the identification of atypical scenarios through a better knowledge management. Risk Anal. 32, 1404–1419. https://doi.org/10.1111/j.1539-6924.2011.01749.x.

Paltrinieri, N., Tugnoli, A., Buston, J., Wardman, M., Cozzani, V., 2013. Dynamic Procedure for Atypical Scenarios Identification (DyPASI): a new systematic HAZID tool. J. Loss Prev. Process Ind. 26, 683–695. https://doi.org/10.1016/j.jlp.2013.01.006.

Patriarca, R., Di Gravio, G., Mancini, M., Costantino, F., 2016. Change management in the ATM system: integrating information in the preliminary system safety assessment. Int. J. Appl. Decis. Sci. 9, 121–138. https://doi.org/10.1504/IJADS.2016.080123.

Qin, S.J., Chiang, L.H., 2019. Advances and opportunities in machine learning for process data analytics. Comput. Chem. Eng. 126, 465–473. https://doi.org/10.1016/j.compchemeng.2019.04.003.

Raviv, G., Shapira, A., Fishbain, B., 2017. AHP-based analysis of the risk potential of safety incidents: case study of cranes in the construction industry. Saf. Sci. 91, 298–309. https://doi.org/10.1016/j.ssci.2016.08.027.

Sakamoto, J., Sato, R., Nakayama, J., Kasai, N., Shibutani, T., Miyake, A., 2016. Leakage-type-based analysis of accidents involving hydrogen fueling stations in Japan and USA. Int. J. Hydrogen Energy 41, 21564–21570. https://doi.org/10.1016/j.ijhydene.2016.08.060.

San Marchi, C., Somerday, B.P., 2012. SANDIA REPORT technical reference for hydrogen compatibility of materials.

Sánchez, A.L., Williams, F.A., 2014. Recent advances in understanding of flammability characteristics of hydrogen. Prog. Energy Combust. Sci. 41, 1–55. https://doi.org/10.1016/j.pecs.2013.10.002.

Scita, R., Raimondi, P.P., Noussan, M., 2020. Previous waves of enthusiasm for hydrogen : will this time be different? Green Hydrogen: The Holy Grail of Decarbonisation?, pp. 5–7.

Sepeda, A.L., 2006. Lessons learned from process incident databases and the process safety incident database (PSID) approach sponsored by the center for chemical process safety. J. Hazard. Mater. 130, 9–14. https://doi.org/10.1016/j.jhazmat.2005.07.061.

Sharda, R., Delen, D., Turban, E., 2018. Business Intelligence, Analytics, and Data Science: A Managerial Perspective, Fourth ed. Pearson, New York, NY.

Souibgui, M., Atigui, F., Zammali, S., Cherfi, S., Yahia, S.Ben, 2019. Data quality in ETL process: a preliminary study. Procedia Comput. Sci. 159, 676–687. https://doi.org/10.1016/j.procs.2019.09.223.

Speight, J.G., 2020. The Refinery of the Future, Second ed. Gulf Professional Publishing, Oxford, UK.

Tamascelli, N., Solini, R., Paltrinieri, N., Cozzani, V., 2022. Learning from major accidents: a machine learning approach. Comput. Chem. Eng. 162, 107786 https://doi.org/10.1016/j.compchemeng.2022.107786.

BARPI, 2022. ARIA Database [WWW Document].https://www.aria.developpement-durable.gouv.fr (accessed 6.30.22).

Tretsiakova-McNally, S., Makarov, D., 2022. HyResponse - Hazards of hydrogen use indoors.

Trujillo, J., Luján-Mora, S., 2003. A UML based approach for modeling ETL processes in data warehouses. Lect. Notes Comput. Sci. 2813, 307–320. https://doi.org/10.1007/978-3-540-39648-2_25.

Tzioutzios, D., Kim, J.-N., Cruz, A.M., 2022. Appetite for natech risk information in japan: understanding citizens' communicative behavior towards risk information disclosure around Osaka Bay. Int. J. Disaster Risk Sci. https://doi.org/10.1007/s13753-022-00415-4.

United States Environmental Protection Agency, 2012. Emergency Planning and Community Right-To-Know Act.

US Chemical Hazard Investigation Board, 2022. CBS Database [WWW Document]. URL https://www.csb.gov/investigations/completed-investigations/?Type=2 (accessed 7.14.22).

US National Transportation Safety Board, 2022. NTSB Database [WWW Document].

US Occupational Safety and Health Administration, 2022. OHSA Database [WWW Document]. URL https://www.osha.gov/pls/imis/accidentsearch.html (accessed 7.14.22).

Ustolin, F., Campari, A., Taccani, R., 2022. An extensive review of liquid hydrogen in transportation with focus on the maritime sector. J. Mar. Sci. Eng. 10, 1–34. https://doi.org/10.3390/jmse10091222.

Ustolin, F., Odsæter, L.H., Reigstad, G., Skarsvåg, H.L., Paltrinieri, N., 2020a. Theories and mechanism of rapid phase transition. Chem. Eng. Trans. 82, 253–258. https://doi.org/10.3303/CET2082043.

Ustolin, F., Paltrinieri, N., Berto, F., 2020b. Loss of integrity of hydrogen technologies: a critical review. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.06.021.

Ustolin, F., Salzano, E., Landucci, G., Paltrinieri, N., 2020c. Modelling liquid hydrogen BLEVEs: a comparative assessment with hydrocarbon fuels. In: 30th Eur. Saf. Reliab.

Conf. ESREL 2020 15th Probabilistic Saf. Assess. Manag. Conf. PSAM 2020, pp. 1876–1883. https://doi.org/10.3850/978-981-14-8593-0.

Ustolin, F., Wan, D., Alvaro, A., Paltrinieri, N., 2021. Risk-based inspection planning for hydrogen technologies: review of currents standards and suggestions for modification. In: 9th Manufacturing Engineering Society International Conference (MESIC 2021). doi: 10.1088/1757-899x/1193/1/012075.

Uth, H.J., Wiese, N., 2004. Central collecting and evaluating of major accidents and near-miss-events in the Federal Republic of Germany - results, experiences, perspectives. J. Hazard. Mater. 111, 139–145. https://doi.org/10.1016/j.jhazmat.2004.02.022.

van Wingerden, K., Kluge, M., Habib, A.K., Ustolin, F., Paltrinieri, N., 2022. Medium-scale tests to investigate the possibility and effects of bleves of storage vessels containing liquified hydrogen. Chem. Eng. Trans. 90, 547–552. https://doi.org/10.3303/CET2290092.

Venetsanos, A.G., Adams, P., Azkarate, I., Bengaouer, A., Brett, L., Carcassi, M.N., Engebø, A., Gallego, E., Gavrikov, A.I., Hansen, O.R., Hawksworth, S., Jordan, T., Kessler, A., Kumar, S., Molkov, V., Nilsen, S., Reinecke, E., Stöcklin, M., Schmidtchen, U., Teodorczyk, A., Tigreat, D., Versloot, N.H.A., 2011. On the use of hydrogen in confined spaces: results from the internal project InsHyde. Int. J. Hydrogen Energy 36, 2693–2699. https://doi.org/10.1016/j.ijhydene.2010.05.030.

Vezirolu, T.N., Barbir, F., 1992. Hydrogen: the wonder fuel. Int. J. Hydrogen Energy 17, 391–404. https://doi.org/10.1016/0360-3199(92)90183-W.

Wada, Y., Katoh, K., Abe, S., Owa Heisig, K., Ogata, Y., 2007. Relational information system for chemical accidents database (RISCAD) with analysis of hydrogen accidents. In: Proceeding of the International Conference on Hydrogen Safety ICHS.

Weiner, S.C., Fassbender, L.L., 2012. Lessons learned from safety events. Int. J. Hydrogen Energy 37, 17358–17363. https://doi.org/10.1016/j.ijhydene.2012.03.152.

Weiner, S.C., Kinzey, B.R., Dean, J., Davis, P.B., Ruiz, A., 2007. Incident reporting: learning from experience. In: Proceedings of the International Conference of Hydrogen Safety ICHS.

Wen, J.X., Marono, M., Moretto, P., Reinecke, E.-.A., Sathiah, P., Studer, E., Vyazmina, E., Melideo, D., 2022. Statistics, lessons learned and recommendations from analysis of HIAD 2.0database. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2022.03.170.

West, M., Al-Douri, A., Hartmann, K., Buttner, W., Groth, K.M., 2022. Critical review and analysis of hydrogen safety data collection tools. Int. J. Hydrogen Energy 47, 17845–17858. https://doi.org/10.1016/j.ijhydene.2022.03.244.

Woodtli, J., Kieselbach, R., 2000. Damage due to hydrogen embrittlement and stress corrosion cracking. Eng. Fail. Anal. 7, 427–450. https://doi.org/10.1016/S1350-6307(99)00033-3.

Wu, D.D., Chen, S.H., Olson, D.L., 2014. Business intelligence in risk management: some recent progresses. Inf. Sci. 256, 1–7. https://doi.org/10.1016/j.ins.2013.10.008.

Xie, Q., Freeman, R.B., 2019. Bigger than you thought: China’s contribution to scientific publications and its impact on the global economy. China World Econ. 27, 1–27. https://doi.org/10.1111/cwe.12265.

Yoon, H., Lee, H., Moon, I., 2000. Quantitative business decision-making for the investment of preventing safety accidents in chemical plants. Comput. Chem. Eng. 24, 1037–1041. https://doi.org/10.1016/S0098-1354(00)00531-7.