Lesson learned from H2-related incidents: criticality of maintenance operations

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The need to address climate change and global warming is overgrowing: decarbonising the industrial and energy sectors, which are significant contributors to greenhouse gas emissions, has become a top priority. In this regard, hydrogen is eligible to be a leading player in the energy transition process as its combustion is carbon neutral. It is expected to progressively replace fossil fuels, penetrating economies, and generating interest from the public. However, the unique characteristics of hydrogen, such as high flammability and ability to permeate, interact with and embrittle materials, require further investigation related to safety aspects. It is crucial to address these issues to ensure the safe and sustainable implementation of hydrogen technologies in various industrial and energy applications, making the spread of hydrogen technologies easier. In this regard, besides clarifying the possible hydrogen hazards and incident outcomes from the uncontrolled release of hydrogen, the development of preventive and mitigation strategies is desirable. The physical integrity of equipment intended for use in hydrogenated environments relies heavily on the importance of conducting inspection and maintenance activities. However, these tasks may also have a negative effect if the execution is incorrect or incomplete. This paper shows the results of an investigation on events collected in the new Hydrogen-related Incident Reports and Analyses (HIRA) database, which was developed from HIAD 2.0 and MHIDAS. Many causes can contribute to the occurrence of an undesired event. This study focuses on maintenance-related accidents. Statistical results are extracted from the database together with a deeper analysis of these events. Lessons learned are provided regarding maintenance errors and lack of maintenance, which leads to material or component failure. The contribution of human errors is also explored. The overall purpose is to raise awareness by making everyone realise how significant developing maintenance plans and training operators is to facilitate the widespread use of hydrogen in new industrial sectors without being affected by its hazardous properties.

KEYWORDS: Hydrogen safety, Data accident analysis, Maintenance criticality, Human errors

Introduction

The urgency to address climate change and global warming is growing rapidly: the industry and the energy sector must be decarbonised. According to (IEA, 2021), hydrogen and hydrogen-based fuels, together with energy efficiency, behavioural change, electrification, renewables, and Carbon Capture Utilization and Storage (CCUS), are key pillars of decarbonising the global energy system. The number of countries announcing pledges to achieve net zero emissions over the coming decades continues to grow. The significance of hydrogen in achieving the Net Zero Emissions Scenario becomes evident from its growing contribution to Total Final Energy Consumption (TFC): in 2020, hydrogen and hydrogen-based fuels made up less than 0.1% of TFC. However, projections show that by 2030, they are expected to account for 2% of TFC, and by 2050, this share is set to increase substantially to 10% (IEA, 2021). Heavy industries, such as steel manufacturing, chemical production, heavy-duty road transport, shipping, and aviation represent the hard-to-decarbonise sectors where hydrogen can be a crucial fuel since it is not toxic, and its combustion does not produce any CO_2 emission. Hydrogen has already been used in many industrial sectors, such as refining, ammonia and methanol production. The demand for hydrogen has grown more than threefold since 1975 and continues to rise (IEA, 2019).

Nevertheless, its implementation in several sectors as an energy carrier on a large scale faces many safety issues. It is highly flammable (with a flammability range of 4 – 75% in air), explosive, and has low minimum ignition energy (i.e., 0.02 mJ) (Nicoletti et al., 2015). More specific hazards are related to the peculiar storage conditions required since it is the lightest existing substance, with a density of 0.0899 kg/m^3 at 0 °C and 1 atm. Transporting large quantities of fuel under these conditions is not feasible: compression or liquefaction are required to increase its storage capacity. The compression process up to 700 bar increases the density up to 40 kg/m^3; the liquefaction process at -253 °C can allow to reach 70.9 kg/m^3 (Hassan et al., 2021). Depending on the storage type, different final unwanted scenarios may occur. Furthermore, hydrogen tends to degrade the mechanical properties of the equipment it comes into contact with due to its capability of permeating and embrittling most structural materials (Abohamzeh et al., 2021). Hydrogen-induced material damages are long-known phenomena in material science, and they are responsible for numerous equipment failures, leading to subsequent releases of hazardous substances. Over the years, these characteristics of hydrogen have caused several undesired events with severe consequences for equipment, humans, and the environment. Whenever a critical event is mentioned, reference can be made to the bow-tie diagram that sees the causes on the left and the consequences on the right (Delvosalle et al., 2006).

Several studies have been made to gain knowledge about consequence analysis in the case of hydrogen-related critical events. However, besides predicting the impact area of a possible incident, the reduction of the probability of undesired events is essential. In this regard, improving preventive strategies, such as maintenance and inspection activities, is required. On the other hand, maintenance may be critical and harm barrier performance if the execution is incorrect, insufficient, delayed, or excessive. In addition, it can be a triggering event, which exposes the operator to further risks (Okoh and Haugen, 2013).

Maintenance activities are generally considered as prevention measures in the typical representation of a critical event through the bow-tie diagram. Figure 1 shows how maintenance can contribute to the occurrence of an event. Some undesired situations are caused by the failure of components or materials due to lack of maintenance, bypassing the preventive safety barrier. In other cases, maintenance operations become the primary cause of the event: incorrect replacement of a component or missing the isolation of the line under repair can cause adverse events. Thus, it is essential to develop a balanced prevention program to avoid unwanted events due to lack of maintenance and, simultaneously, not include unnecessary operation, being a critical activity.

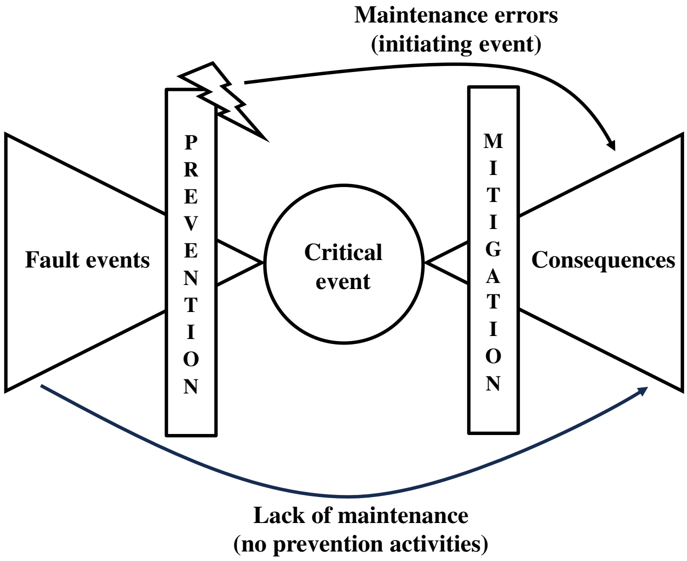

Figure 1 - How maintenance impacts on incident/accident management.

Awareness of past mistakes is of utmost importance if the willingness is to implement hydrogen in new technologies, leading to emerging risks. Hence, collecting data through online databases, reports, and publications is fundamental. The Hydrogen Incident and Accident Database (HIAD 2.0), developed and updated by the Joint Research Center of the European Commission, is the main source of hydrogen undesired events and collects 689 incidents, accidents, and near misses. In addition, the British Major Hazard Incident Data Service (MHIDAS), developed by the Safety and Reliability Directorate (SRD) of the UK Atomic Energy Authority (AEA) and the United Kingdom Health and Safety Executive (UK HSE), is a reliable source of data on major hazard events counting more than 9000 events. However, this study considers a new well-structured hydrogen-related incidents database called Hydrogen-related Incident Reports and Analyses (HIRA) (Campari et al., 2023b).

In light of this, the analysis of this database is conducted focusing on maintenance-related undesired events. The selected events are thoroughly investigated to understand the role of maintenance. The aim is to emphasise the importance of conducting properly these activities. Among the issues related to these crucial operations, the contribution of human errors is highlighted since even small mistakes may result in serious events with severe consequences.

This paper is structured as follows. The "HIRA database" section describes the new database used for this investigation, clarifying the reasons for the development. The "Methodology" section explains the procedure adopted in this work. Firstly, the maintenance-related events are analysed using different approaches to obtain statistical results. Then, the emphasis is placed on how maintenance can be involved in these scenarios: human errors during maintenance operations are frequent. The "Results and Discussion" section shows and comments on the outcomes of the analysis, focusing on some relevant events. Finally, the "Conclusion" section summarises the main findings of this study.

HIRA database

Hydrogen-related Incident Reports and Analyses (HIRA) is a well-structured database for hydrogen-related undesired events. HIAD 2.0 and MHIDAS are the primary sources of information for this new repository tool. On the one hand, HIAD 2.0 (HIAD 2.0, 2023) is a multi-use platform for deriving best practices for hydrogen safety and lessons learned from previous undesired events. It includes a data entry form with numerical, categorical, and textual fields. The main drawbacks of this database are the scarcity of quantitative information, the lack of a common taxonomy, and the ambiguous definition of predetermined categories. On the other hand, MHIDAS is a non-hydrogen-specific safety database whose records are not included in HIAD 2.0. HIRA aims to overcome the main limitations of the previous databases by describing each undesired event with a set of 43 numerical and categorical features, referring to the components involved, the causes and consequences of the event, the physio-chemical properties of the released substances, and the presence of safety barriers. These features have been selected to minimise the loss of information, ensure immediate understanding of the events, and allow automatised data analysis. It is worth noting that HIRA has restrictive inclusion criteria to ensure data quality and the relevance of the collected events. All the unwanted events that occurred in the H_2 value chain and involved hydrogen-specific equipment (e.g., electrolysers or fuel cells) or other components for hydrogen handling and storage (e.g., pipes, flanges, valves, compressors, etc.) were included in the database. In contrast, all the events where hydrogen was a by-product of undesired reaction (e.g., in refineries, ammonia and chlorine production plants, manufacturing industries, etc.), along with car incidents not directly caused by the failure of hydrogen-fuelled vehicles, were excluded. In its latest version, HIRA comprises 325 events that occurred in the H_2 value chain (Campari et al., 2023b).

Methodology

Step 1: selection of maintenance-related events

The study relies on information in the abovementioned Hydrogen-related Incident Reports and Analyses database. Maintenance-related undesired events are selected through Business Analytics (BA) tools. Firstly, events with 'maintenance error' as the primary cause are selected. Based on the definition of primary cause classification, it is possible to select all the events that occurred due to an error during the maintenance procedures of a component or system. However, maintenance can be involved and responsible for unwanted events differently. Besides maintenance errors, many events occurred due to a lack of maintenance activities. An overview of maintenance-related events was obtained by reading all the information available for each case in the database, allowing to understand how maintenance contributed to each situation. Three main categories are selected:

- lack of maintenance (i.e., events that could have been avoided through preventive activities);
- human error during maintenance activities;
- generic error during maintenance activities.

Creating this new dataset containing only those events in which maintenance played a role allows the BA tools to create charts and graphs and provide statistical results. The most critical stages of the hydrogen supply chain are highlighted together with the components more subjected to failures and malfunctioning.

Step 2: investigation of human error in maintenance-related events

Developing a lesson learned when the cause of the event is a human error is challenging since many factors can contribute. In fact, over the years, much attention has been paid to this aspect of incident and accident management. In this regard, Human Reliability Analysis (HRA) is a systematic means of evaluating human contribution to risk. The primary goal of HRA is to identify, quantify, and mitigate the likelihood of human errors occurring during specific tasks or operations. By understanding the factors that can lead to human errors, organisations can design more robust processes and systems less susceptible to failures caused by human performance. In this regard, Petro-HRA (Bye et al., 2017) is a method available since 2017 as a result of the homonymous project funded by the Research Council of Norway. Considering the human's individual characteristics, environment, organisation, or tasks that specifically decrease or increase human performance, nine Performance Shaping Factors (PSF) are identified and considered responsible for increasing or decreasing the likelihood of human error:

- **Time** considers the influence on human error probability based on the difference between available and required time. The operator should have enough time to detect, diagnose, decide, and act before the point of no return with adverse consequences.
- **Threat Stress** is the response to perceived physical or psychological harm. For instance, an operator can feel this stress if his or other people's life is in danger.
- **Task Complexity** is the difficulty level of performing a task within a specific context.
- **Experience/Training**: the first refers to how often the operator has already handled the task or the scenario in question; the second refers to the acquired knowledge and skills, that are required to perform a specific task.
- **Procedures** consider the clarity of the documents representing the decisions and action steps to be performed and the possibility that the operator does not follow these documents.
- **Human-Machine Interface** involves the quality of equipment, controls, hardware, software, etc.
- **Attitudes to Safety, Work, and Management Support**: the first refers to an individual's positive or negative evaluation of performing safety-related behaviours, contributing to a safety-conscious work environment. The second refers to the reception of explicit support from managers for performing tasks. This support includes allowing shutdowns for safety without fear of negative consequences.
- **Teamwork** refers to the involvement of all members in the activities.
- **Physical Working Environment** refers to the equipment used, accessibility, and working conditions of the person performing the task.

In this study, the Petro-HRA methodology is not used to quantify the human contribution to risk. Undesired events that the above analysis shows to be caused by human error are investigated from the perspective of associating a Performance Shaping Factor when enough information is available.

Results and discussion

Maintenance activities are of utmost importance in a plant to ensure that industrial equipment and machinery are in optimal working condition. Reliability analyses are crucial to prevent unexpected breakdowns leading to costly downtime and production losses. Moreover, regular maintenance helps identify and rectify potential safety hazards. Malfunctioning equipment can be dangerous to both employees and the environment. Hence, a proper maintenance strategy is even more necessary in high-risk sectors. However, maintenance has also been involved in numerous events over the years. Shifting the focus to hydrogen incidents and accidents, maintenance-related undesired events were selected in the HIRA database.

Sorting the events through the primary cause classification was insufficient since not all the component failure relies on lack of maintenance, while the maintenance error was more reliable in the selection. The analysis of the database led to the collection of 76 undesired events, categorised according to maintenance's role in the event. Figure 3 shows the impact of maintenance on the unwanted events over the years: for each year, the blue column represents the total number of events collected in the HIRA database; the red column represents the maintenance-related events.

This database is not an exhaustive collection of all hydrogen-related undesired events. It is likely, even almost sure, that many undesirable events that have occurred over the years have not been reported. For this reason, the percentage of maintenance-related events over the total is more meaningful, and it is pictured by the grey column, which refers to the secondary axis on the right-hand side of the graph. This ratio does not show a trend over the years. Conversely, the average number of undesired events over the last two decades has decreased thanks to improved safety design and operative provisions (Wen et al., 2022). This scenario suggests that a few measures should be taken: in the coming years, there will be an increasing rollout of hydrogen systems, with hydrogen playing a leading role in new industrial sectors. Inevitably, the absolute number of undesired events will rise, but the aim should be to keep the number of events in which maintenance plays a role as low as possible. However, if effective maintenance plans are not developed, events due to a lack of preventive activities will increase. Similarly, if clear operating procedures and operator training are not provided, issues due to errors during maintenance will become more common.

Adding to the database the further column, which categorises how maintenance contributed to the events, leads to distinguishing how many unwanted events could have been avoided by more effective maintenance management (lack of maintenance) and how many were caused by errors during those operations. Figure 2 shows the distribution: the share of events that were due to lack of preventive measures is around 50%, just as much as the fraction of errors during maintenance operations. Among the second category, 26% of the events occurred due to human error. In comparison, 19% of the total events are attributable to generic errors whose causes have not been defined because of missing information in the reports.

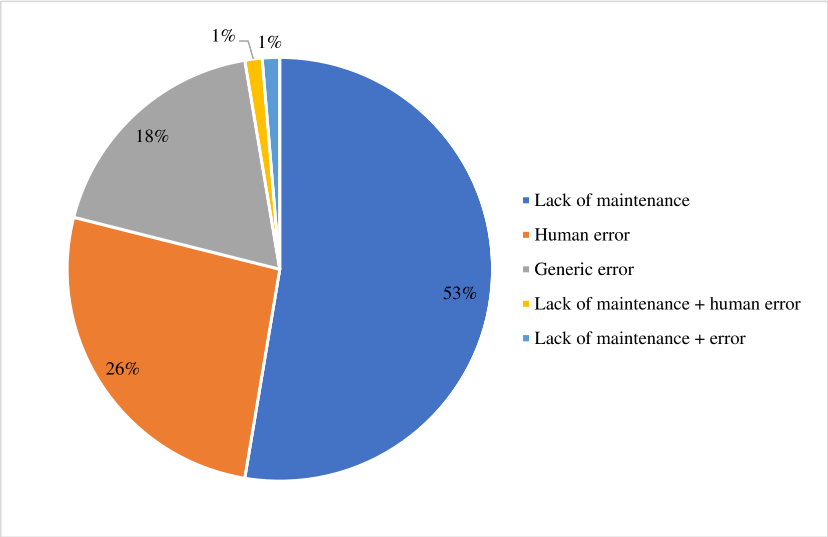

Figure 2 - Causes of maintenance-related undesired events.

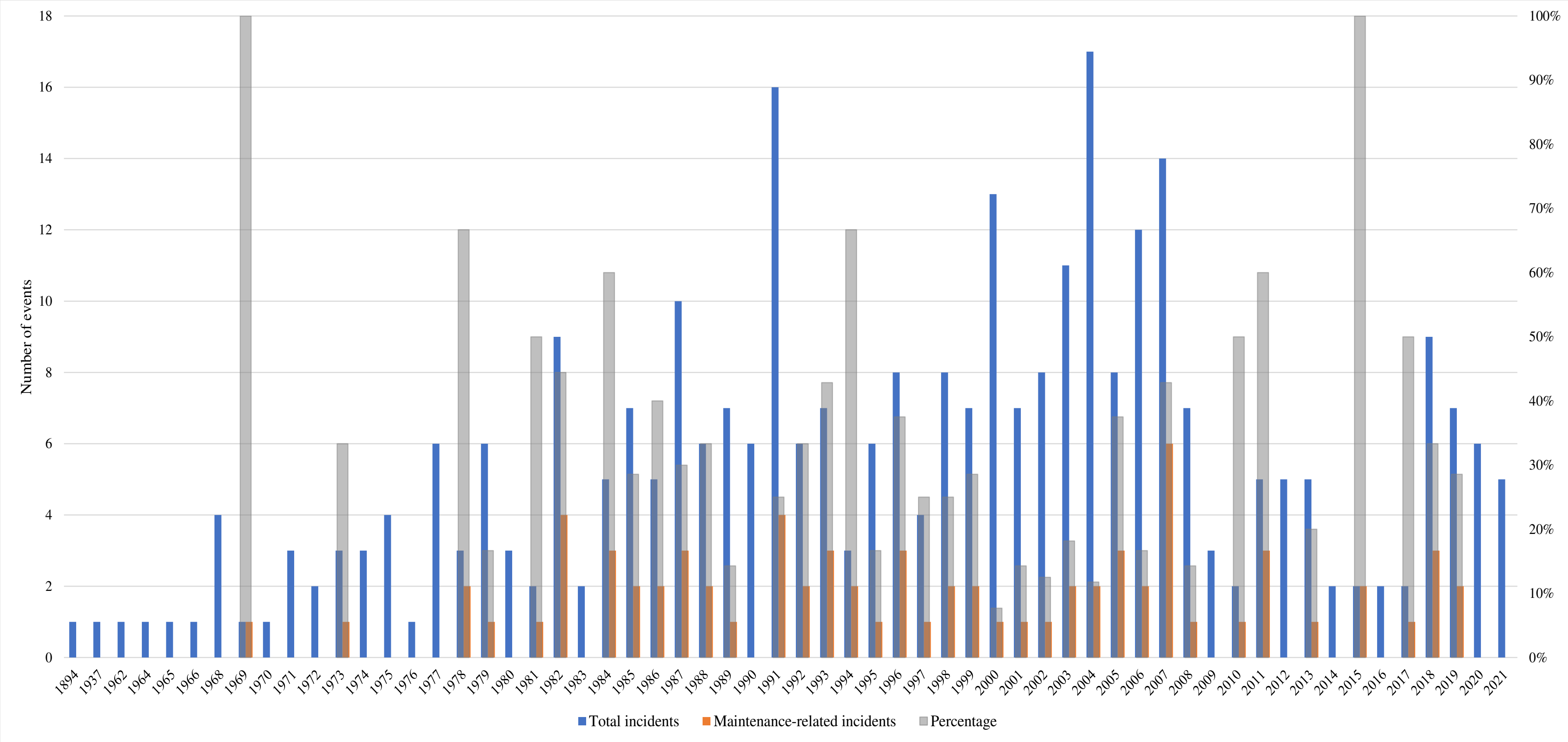

Figure 3 - Maintenance-related events over the years.

Figure 4 shows the partition of undesired events in the stages of the hydrogen value chain. Hydrogen can be produced employing different techniques: reforming, gasification, pyrolysis, thermochemical cycles, fermentation, and electrolysis are some of them (Ustolin et al., 2020). After its production, it should be stored effectively; compared with other fuels, this substance requires a larger volume if stored in normal conditions. Hence, several methodologies are adopted to store hydrogen: the most common are compression, cryo-compression, and liquefaction. Physical adsorption and chemical-bound absorption can also be used. Then, hydrogen can be transported and distributed to several applications through pipelines, truck trailers, trains, or ships. Maintenance-related undesired events are by far the most common in hydrogen transportation and distribution. Indeed, this is a highly tricky phase due to the ability of hydrogen to permeate, degrade, and embrittle most metallic materials. This result has already been noted in the study conducted on HIAD 2.0 (Campari et al., 2023a), and it becomes more evident if only maintenance-related events are taken into consideration. Hydrogen-induced material failures could often have been avoided if maintenance activities were carried out.

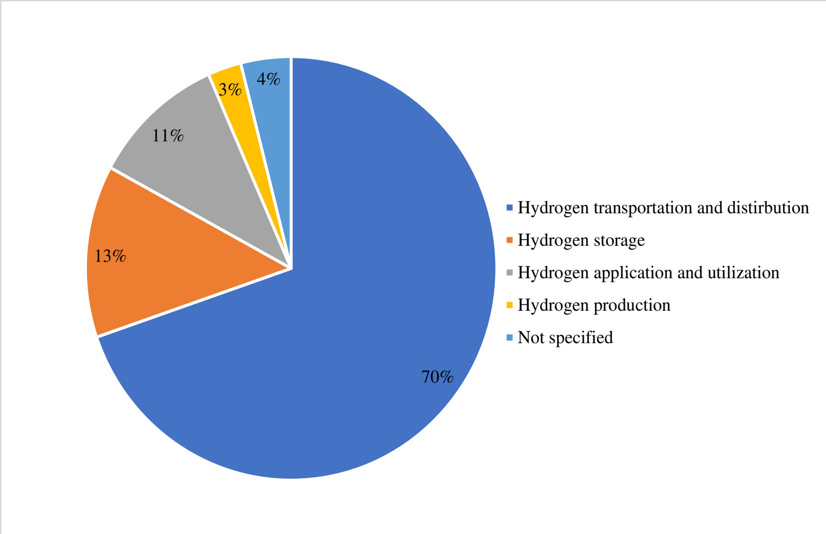

Figure 4 – Maintenance-related undesired events in different application stages.

Figure 5 shows which components are most frequently involved in unwanted events. The result is consistent with the findings highlighted and explained in Figure 4. The hydrogen transportation and distribution technique most spread is through pipelines (Ustolin et al., 2020). Since it is the most critical stage of its value chain, it is coherent that pipelines are the most affected items. This analysis is essential from the perspective of expanding the use of hydrogen and spreading it in industrial sectors beyond the chemical and petrochemical industry, which appears to be the most involved in the events collected in this database. Understanding which components require more attention is crucial when developing new systems: pipelines, valves and joints, such as flanges, rings, and seals, are widespread components in a plant and knowing that they are critical is the first step for developing ad-hoc safety measures.

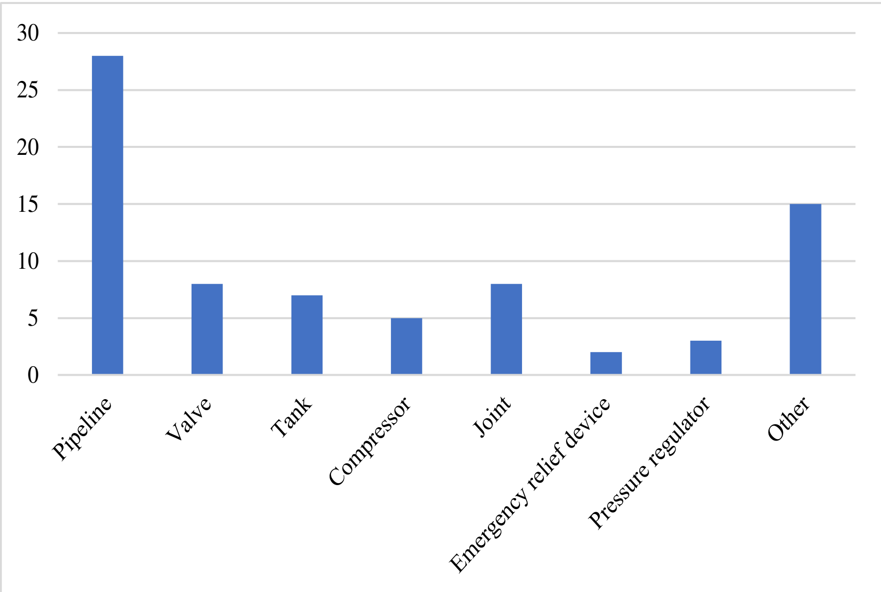

Figure 5 - Components involved in maintenance-related undesired events.

Over several years, international efforts have been initiated to develop regulations, standards and codes required for introducing hydrogen energy systems. As of today, only a few standards are available for managing the components in hydrogen technologies, and they mainly refer to refuelling stations (ISO Standard, 2019, 2018). The American Petroleum Institute provided guidelines for non-destructive examination and other methods for detecting, monitoring, characterising, sizing and determining the severity or the extent of material damages (API, 2019). The most effective techniques to detect and monitor the degradation are provided for each hydrogen-induced damage. Nevertheless, the choice of the optimal inspection frequency is generally entrusted to the component supplier, who often lacks detailed information on failure rates, considering the relatively recent spread of these technologies and the resulting lack of operational experience.

Lack of maintenance: lessons learned

Among the 76 events categorised as maintenance-related, 42 can be attributed to lack of maintenance. An in-depth investigation on this topic has already been provided by analysing the HIAD 2.0 database, the primary source of hydrogen incidents (Campari et al., 2023b). Material failures of equipment directly or indirectly exposed to hydrogen caused some events: more specifically, corrosion-related degrading mechanisms, such as atmospheric corrosion, sulfuric acid corrosion, and corrosion fatigue, were responsible for several pipelines' failures; mechanical and thermal fatigue were also relevant for other events. In these cases, hydrogen-metal interaction was not the primary cause of the undesired events but helped to accelerate and facilitate the failure of the components. On the contrary, some events have occurred due to hydrogen-induced damages: hydrogen embrittlement, hydrogen-induced cracking (HIC), hydrogen-induced stress corrosion cracking (HISC) and high-temperature hydrogen attack (HTHA) have often been found to be responsible for recorded events. All these events occurred before standard and codes, such as the Technical Report ISO/TR 15916 for hydrogen-materials compatibility, were published (ISO Standard, 2017).

Moreover, several equipment in operation have been designed before these publications; other problems of the same type are expected to occur if no attention is given to maintenance activities. Even some of the most recent undesired events are due to a lack of such prevention activities. In 2018, a jet fire occurred in a laboratory in France after a leakage due to the failure of a pressure regulator (ID 918 in HIAD 2.0). Still, the report mentions that better procedures for adequately monitoring materials and equipment could have helped. Hence, developing a proper methodology for maintenance planning is imperative.

Errors in maintenance: lessons learned

Among the 76 undesired events categorised as maintenance-related, 36 are attributable to errors during maintenance operations. It is a rather high number considering that maintenance activities are not carried out daily. The relatively high share of undesired events associated to maintenance operations justifies the interest towards this topic and stimulates further investigations of the root causes of these events.

A smaller fraction of these is labelled as generic errors in Figure 2: in most cases, missing information cannot lead to an in-depth investigation of the origin of the errors. In the descriptions, it is only mentioned that errors caused the unwanted event during maintenance activities. A relevant example is the explosion and fire that occurred in the Sodeguara refinery in Japan in 1992 (ID 939 in HIAD 2.0), where several maintenance errors led to the breaking-off of the lock ring of the channel cover of a heat exchanger and the blowing-off of the lock ring, channel cover and other parts (Okoh and Haugen, 2013).

It can also happen that more than one error contributes to the event: in an industrial plant in the USA in 2011 (ID 939 in HIAD 2.0), a pipeline not properly maintained started to leak due to a material failure; during the repairing works, the operators unintentionally ignited hydrogen through the friction sparks produced by the operations, leading to a powerful explosion. In this case, there was a combination of leak of maintenance and maintenance error.

The analysis of events caused by human errors has been conducted using performance shaping factor developed in Petro-HRA. Table 1 summarises the human error-related undesired events by associating the responsible PSF with each one, highlighting the application stage of the hydrogen value chain and the components involved in the event. The most widespread factor accountable for having caused unwanted events was "procedure". However, it is hard to state whether there was a problem with the unclarity of the documents or a lack of observance of the steps to be followed by the operator.

The most common initiating event is the formation of an explosive mixture. For instance, in a chemical plant in France in 2013 (ID 935 in HIAD 2.0), an incorrect isolation of a hydrogen pipeline allowed air to come into contact with hydrogen during maintenance work. The wide flammability range and the low minimum ignition energy of the substance led easily to an explosion. ISO 19880-1:2020 acknowledged this issue and specified that hydrogen equipment should be adequately isolated during maintenance activities (ISO Standard, 2020). Positive isolation involves the complete separation of one part of the plant or equipment from other parts of the system; proved isolation involves valves where the effectiveness of valve closure can be confirmed via vent points.

Lack of experience in handling this substance is also a source of human errors. All employees approaching hydrogen or materials capable of evolving hydrogen must receive safety training (Pacific Northwest National Laboratory, 2022). Management must guarantee that workers can access appropriate training to perform their tasks safely. In a chemical plant in the USA in 2005 (ID 117 in HIAD 2.0), a jet fire occurred after a leakage due to a material failure. A maintenance operator mistakenly replaced an alloy steel elbow with a carbon steel part in a high-pressure, high-temperature line. The failure was induced by a high-temperature hydrogen attack (HTHA). In this case, the reason was the unawareness of the maintenance contractor about the material properties differences in this environment.

Table 1 – Association of Performance Shaping Factor to maintenance and human error related events. The Event ID number corresponds to HIAD 2.0 database except for the last one which refers to MHIDAS.

Event ID	Date	PSF responsible	Application stage	Component
ID 47	31.12.1969	Experience/training + procedures	Hydrogen application and utilisation	Anaerobic chamber
ID 52	10.04.1982	-	Hydrogen transportation and distribution	High pressure injection pipe
ID 85	25.05.2007	Human-machine interface	Hydrogen application and utilisation	Compressor
ID 117	28.07.2005	Experience/training	Hydrogen transportation and distribution	Pipeline
ID 256	21.05.1993	Procedure	Hydrogen transportation and distribution	Coolant pipeline
ID 299	04.07.2003	Procedure	Hydrogen storage	Cylinder
ID 345	16.06.2003	Teamwork	Hydrogen transportation and distribution	Pipeline
ID 475	01.06.2019	Attitudes to safety, work and management support	Hydrogen transportation and distribution	Shut-off valve
ID 561	04.08.2019	Procedure	Hydrogen production	Generator
ID 562	06.07.1985	Procedure	Hydrogen transportation and distribution	Pump gasket
ID 673	28.10.1996	Procedure	___	Furnace
ID 717	10.08.2004	-	Hydrogen application and utilisation	Anaerobic chamber
ID 718	05.12.1998	Procedure	Hydrogen application and utilisation	Furnace
ID 749	23.04.1987	Task complexity	Hydrogen transportation and distribution	Valve
ID 773	03.08.1987	Experience/training	Hydrogen transportation and distribution	Pipeline
ID 912	23.02.1989	Procedure	Hydrogen transportation and distribution	Bolt
ID 935	17.01.2013	Procedure	Hydrogen transportation and distribution	Pipeline
ID 943	20.09.2011	Procedure	Hydrogen transportation and distribution	Flange
ID 988	24.09.2019	Procedure	Hydrogen transportation and distribution	Flange
ID 3227B	01.10.1981	-	Hydrogen transportation and distribution	Joint

Conclusion

The intention to use hydrogen in a variety of new applications requires the development of safety practices: learning from past incidents and accidents is undoubtedly a valuable way to achieve this goal. This study investigates the 325 events collected in the new HIRA database. Among the matters to be explored, inspection and maintenance operations are of the utmost importance to guarantee the safe operability of hydrogen systems. Hence, the initial goal was to identify maintenance-related undesired events.

The time-based analysis of these events showed that there has been no decrease in the occurrence of this type of undesired events. If no corrective measures are taken, these situations will inevitably increase since the possibility of finding hydrogen in different industrial sectors is expected to increase in the forthcoming years.

The most affected stage of the hydrogen value chain is transportation and distribution; the most affected components are pipelines. When developing maintenance plans, these outcomes should be considered, and pipelines should be assessed as high-risk components.

Reading the descriptions of these events led to the creation of a new dataset of 76 events, which were labelled based on the role of maintenance in the events. Slightly more than half occurred because of lack of maintenance; the interaction of hydrogen with metals is a well-known issue, but a proper plan to handle it is still missing and should be a priority. The other half of the collected unwanted events are attributable to maintenance errors: among these, 20 events were caused by human errors. This cause is not entirely avoidable, but its contribution could certainly be reduced if operators were better trained.

Acknowledgment

This work has received fundings from the European Union Horizon 2020 research and innovation program under the Grant Agreement No. 101092153. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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