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Safety Lessons From HRS Events Analysis

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The global energy landscape is undergoing a profound transformation, driven by the urgent need to combat climate change and reduce greenhouse gas emissions. At the forefront of this transition stands hydrogen, an element that has gained increasing attention for its potential to revolutionize the way energy is produced, stored, and utilized (European Comission, 2018). Yet, despite the world's rapid evolution, safety remains an unceasing concern, not just an ethical imperative but a strategic necessity. The safe development and utilization of hydrogen technology must remain at the head of the efforts to harness the full potential of hydrogen as a clean energy source (Salehi et al., 2022). In this sense, accidents and incidents, unfortunate as they may be, offer invaluable knowledge that when considered, can lead to safer environments, reduced risks, and a more conscientious society. Every accident presents an opportunity for organizations and regulators to learn and take actions for improving operational safety (Dodshon and Hassall, 2017; Reason, 1997). In the context of hydrogen transport, the safety of hydrogen refuelling stations (HRSs) is a public concern that has to be addressed for its successful development (Wen et al., 2022). The use of accident experiences in HRSs for enhancing safety is one of the purposes of this research. In essence, the analysis of events included in different international accident databases (Table 1) yields valuable safety insights (Campari et al., 2023).

Table 1. Database information.

Database	Description
Hydrogen Incident and Accident Database 2.0 (HIAD 2.0)	Developed by the Joint Research Centre (JRC) of the European Commission (EC). Records worldwide hydrogen-related events and near-misses.
Hydrogen Tools Lessons Learned database (H2 LL)	Developed by the Pacific Northwest National Laboratory, supported by the U.S. Department of Energy. Includes hydrogen safety event records and shares lessons learned.
The High Pressure Gas Safety Institute of Japan database (KHK)	Developed by the High Pressure Gas Safety Institute of Japan at the request of the Ministry of Economy, Trade, and Industry. Records incident information related to high-pressure gases and hazardous substances in Japan.
Analysis, Research and Information on Accidents database (ARIA)	Developed by the Bureau for Analysis of Industrial Risks and Pollution (BARPI) within the Ministry of Environment/General Directorate for Risk Prevention. Catalogues industrial and technological events.

The present research has adopted a systemic approach, which considers that the unit of analysis is made up of a hierarchy of complex systems mutually interacting and influencing each other (Rasmussen, 1997). This perspective underlines the importance of moving beyond the technical focus to integrating a holistic view. The review of the different databases identified a total of 211 events occurred in HRSs during the period 2005-2022. Events were analysed using a protocol aimed at highlighting the main contributing factors (Navajas et al., 2023) that also allowed the collection of the immediate actions implemented by the HRSs in response to abnormal events. Those actions, essentially "countermeasures," aimed to prevent, reduce, or mitigate potential threats or harm. The protocol permitted their categorization within a socio-technical framework encompassing technical, human-organizational, and inter-organizational levels (Table 2).

Table 2. Socio-technical levels.

Level	Description of the actions	Example
Technical	Typically related with the design, development, implementation, and maintenance of technical solutions and infrastructure.	Replacement of the hoses (ID. 2018-705 KHK)
Human-organizational	Actions involve human performance, strategic planning, policy development, and overall management of the organization's resources.	Operators training (ID. 2017-515 KHK)
Inter-organizational	Actions extend beyond the boundaries of the HRS (partnerships, alliances, supply chain interactions...)	Car manufacturer re-design (ID. 1018 HIAD 2.0)

Despite historical analyses of major industrial accidents such as the Bhopal (1984) and Chernobyl (1986) catastrophes have emphasized the multi-faceted nature of incidents involving complex systems, a preliminary analysis of 70 HRSs events shows a persistent trend towards technical-level corrective measures (Figure 1).

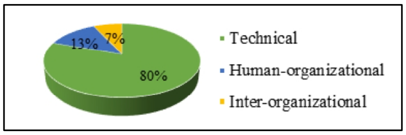

Fig. 1. Countermeasures type.

A deeper examination of the information included in the databases facilitates the classification of this predominant technical countermeasures into distinct typologies. The findings reveal a significant prevalence of corrective measures characterized by reactive interventions such as the readjustment of seals or the replacement of shut-off valves and O-rings. Notably, there is a discernible shift in recent incidents towards adopting a more comprehensive and systemic approach to corrective measures (i.e. ID. 2021-560 KHK Inclusion of error prevention techniques; ID. 2021-528 Definition of responsibilities). This expanded perspective incorporates measures that extend beyond immediate rectification, encompassing regulatory modifications and the exploration of underlying causal factors. The incorporation of such holistic strategies reflects a shifting trend in addressing incidents, particularly within high-risk industries fostering genuine organizational learning.

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