

EUROPEAN HYDROGEN SAFETY PANEL

2026

**Statistics, lessons learnt
and recommendations from
the analysis of the
Hydrogen Incidents and
Accidents Database (HIAD
2.4)**

DOCUMENT HISTORY

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1 INTRODUCTION

The Hydrogen Incidents and Accidents Database (HIAD) was initially developed in the frame of HySafe, an EC co-funded Network of Excellence in the 6th FrameWork Programme by the Joint Research Centre of the European Commission (EC-JRC). It was designed as a systematic collection of data on hydrogen-related undesired events, which is to be shared online to serve extraction of returns of experience, and to support a safe deployment of hydrogen systems. The JRC performed a first major upgrade of the database structure to HIAD 2.0 in 2016, with the support of the Fuel Cells and Hydrogen 2 Joint Undertaking (now the Clean Hydrogen Joint Undertaking).

Since the launch of the European Hydrogen Safety Panel¹ (EHSP) initiative in 2017 by FCH 2 JU, the EHSP Task Force 3 has worked with JRC on HIAD collection and assessment. A first report to summarise the findings of the analysis was published by FCH 2 JU in September 2019. The joint EHSP - JRC effort continued in the following years, resulting in increase of the total number of incidents from 272 in 2018 to 593 in March 2021², and of the overall quality of the data. A second report was published in 2021, based on the assessment of all validated events. The increased number of incidents has also made it viable to extract more reliable statistics².

The present report is the 3rd of the series, which has been updated with the assessment of events added by JRC in the 2022-2025 period under consideration of the upgraded structure of HIAD. To avoid confusion about version numbers, it has been decided to refer to the database as HIAD (without a version number) when describing general issues. The present analysis covers statistics, lessons learnt and recommendations on 898 events out of the 1220 events which were in the public available version of HIAD 2.4 in May 2026. Due to the limited time available, it was decided to leave the remaining events to be analysed next year together with any new events that are continuously being added to HIAD. The statistics have included the 598 events that were in HIAD 2021 and included in our previous Report plus 305 newly added events in HIAD 2.4. Considering that there are a considerable number of newly added events involving Liquid Hydrogen (LH2), the Lessons Learnt and Recommendations have been updated with a specific sub-section about LH2.

¹ <https://ehsp.eu/>

² <https://ehsp.eu/hydrogen-safety-reports/>

The report is organized as follows: Following this Introduction, Chapter 2 outlines the sources of information used by HIAD, the analysis procedures and methodology. The descriptions about the analysis procedures which were previously scattered in other Chapters have now all been consolidated in this Chapter. An overview of the events is given in Chapter 3, followed by the statistics derived from the available events in Chapter 4. Chapter 5 discusses the lessons learnt while Chapter 6 presents the recommendations stemming from the analysis. Wherever applicable, the recommendations refer to the EHSP-identified safety principles, which were listed in the “Safety Planning and Management in EU Hydrogen and Fuel Cell projects” report published in 2021, which has been updated in parallel while the present analysis has been underway. Hence, the current analysis has been based on the previously published report while the new report with an additional Safety Principle and will be referred to in our future analysis.

The readers are also recommended to consult the original event description in HIAD, which provides more details³. To facilitate this, the incidents selected as examples in this report refer to their HIAD event identification number in the database.

³ Version HIAD 2.2 is available at <https://minerva.jrc.ec.europa.eu/en/shorturl/capri/hiadpt>. At that page a dashboard is available as well, for an online statistical overview of the most important parameters. New versions of HIAD will be soon available the Knowledge Hub of the Clean Hydrogen JU.

2 DATA COLLECTION, ANALYSIS PROCEDURE AND METHODOLOGY

HIAD is a permanently growing database as new events are being continuously added, validated, and released. At the time of this assessment, it contained 1220 events (as of March 2026). T2.1 the analysis in the present report was conducted for 898 events, which include the events analysed in the 2021 report as well the newly added events during 2022-2025.

2.1 Data collection

HIAD data collection relies on publicly available sources, ranging from online news and post-incident investigation reports up to incident collections and structured databases. Historically, major sources of events in HIAD have been databases dedicated to industrial incidents, such as the French ARIA⁴, the JRC eMARS⁵ and the MHIDAS⁶ hosted by UK IChemE. While the first two are still managed and updated, and regularly consulted by HIAD, the last one was phased out in 2000. For North America, HIAD relies on CBS investigations⁷ and the reports of the Occupational Safety and Health Administration⁸. Specific to Japan, several HIAD data came from the databases RISCAD⁹, no more accessible, and JST¹⁰, covering industrial events up to 2004. Specific to hydrogen used or produced in nuclear facilities, source to HIAD are the US, French and Japanese national regulatory commissions. Several databases and collections dedicated to individual industrial sectors provided additional sources, as well as an increasing number of scientific publications. In the years 2019-20, a joint EHSP-JRC collection effort guaranteed completeness of knowledge transfer from ARIA, eMARS and MHIDAS, contributing also with events from a database of the University of Warwick.

⁴ [ARIA - La référence du retour d'expérience sur accidents technologiques](#)

⁵ [EUROPA - MINERVA Home Page - European Commission](#) (please note that eMARS has been discontinued and will be available on JRC MINEVA platform only till end of 2026)

⁶ [Process Safety Accident Data - IChemE Safety Centre - IChemE](#)

⁷ [U.S. Chemical Safety and Hazard Investigation Board | CSB](#)

⁸ [Home | Occupational Safety and Health Administration](#)

⁹ [RISCAD|Relational Chemical Disaster Database - Sanpo no Hiroba|Industrial Safety Portal Site|Information on Industrial Safety](#)

¹⁰ Japanese Failure Society, [JST Failure Knowledge Database](#)

Despite any completeness efforts, HIAD remained characterised by some bias, due to the scope and characteristics of the sources used, such as an over-representation of stationary, industrial applications, and a geographic imbalance because most of the sources focus predominantly on European and the United States. Although this does not hinder the capacity to extract general conclusions, these biases do influence the percentages of events recorded for different sectors.

Since 2021, JRC has continued the data collection activity, increasing the number of HIAD events up to a total of 1220 at the start of 2026, aiming at reducing the mentioned bias. In terms of technologies, JRC has focused on enriching the dataset with safety knowledge on liquid hydrogen and on hydrogen transport and distribution. Datasets related to these topics were extremely limited in HIAD versions preceding 2021. Now HIAD contains NASA reports of hydrogen incidents, mainly related to liquid hydrogen handling, transport and use, from vintage collection by P.M. Ordin published in 1974¹¹ up to the most recent cases that occurred during the development of the Artemis programme. The Pipeline database of the Hazardous Materials Safety Administration (PHMSA)¹² of the U.S. Department of Transportation (DOT) collects reports on incidents related to transport of hazardous materials, for example by pipelines and road transport¹³. The dataset goes back to the 70's, and companies are committed by the DOT to declare incidents via a harmonised template. HIAD has encoded the hydrogen-related events from PHMSA reported since 1990. Finally, the AIChE H2TOOLS Lesson Learned¹⁴ was used mainly for incidents related to laboratory setups and hydrogen refuelling stations.

JRC has also worked on geographic coverage, by reaching out resources in Asia and other part of the world. The Japanese database maintained by the Gas Safety Institute KHK¹⁵ provided events happened during hydrogen transport and at hydrogen refuelling stations in Japan. Online

¹¹ Ordin, P.M., Review of Hydrogen Accidents and Incidents in NASA Operation, NASA Report NASA-TM-X-71565, 1974.

¹² See entry page [PHMSA: Stakeholder Communications | Home \(dot.gov\)](https://www.phmsa.dot.gov/stakeholder-communications) and the page dedicated to hydrogen: [PHMSA: Stakeholder Communications: Hydrogen \(dot.gov\)](https://www.phmsa.dot.gov/stakeholder-communications/hydrogen) (accessed May 2026)

¹³ PHMSA HAZMAT search entry page at: <https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics>. (accessed May 2026)

¹⁴ [Lessons Learned | H2tools | Hydrogen Tools](#)

¹⁵ High Pressure Gas Accident Cases Database of the High Pressure Gas Safety Association(KHK): https://www.khk.or.jp/public_information/incident_investigation/hpg_incident/incident_db.html (accessed May 2026)

data collections were used to get data from the hydrogen deployments in China. Finally, to guarantee the broadest possible timeline and to offer an historical perspective, the old collection of hydrogen incidents in industry and transport by Zalosh and Short¹⁶ was encoded almost entirely in HIAD.

2.2 Methodology

The assessment of events from HIAD covers three areas:

- Identification of the **cause** of the event
- Characterisation of the event in terms of **severity**
- Assessment of the **lessons learned** by allocation of violated safety principles to the event

All three areas follow a pre-defined systematic, described in the following.

Table 2.1 gives the categories used to characterise the **cause(s)** of an event.

Table 2.1. HIAD events classified by causes

Cause	Description
System design error	The system was not properly designed - for the present boundary conditions - for the use of hydrogen
Material/ manufacturing error	Although the correct component was selected and implemented, it didn't work properly due to material failure or due to a manufacturing error.
Installation error	Although the correct component was selected and implemented, it didn't work properly due to improper installation or maintenance.
Job factors	These involve factors related to the quality of the working conditions, leading to operator error.
Individual/ human factors	These involve factors related to the personal situation of the operator, leading to operator error.
Organization and management factors	These involve factors related to the on-site organization and management, leading to operator error.

¹⁶ R. Zalosh, T. Short, Compilation and Analysis of Hydrogen Accident Reports Final Technical Report, Factory Mutual Research Corporation, FMRC J.1. 4A7NO.RG, RC78-T-54, 1978

The first three categories characterise events caused by hardware failures. "System design error" characterises an event where the plant design wasn't considering the right boundary conditions or the specific requirements for systems involving hydrogen. If the system had been properly designed but failure of components still occurred, this can be attributed either to a failure of material, a manufacturing error, or to improper installation or maintenance.

The second three categories characterize events caused by operator error. Mistakes being made are attributed three factors: "Job factors" support misbehaviour due to a poor quality of the working conditions. "Individual/human factors" characterise errors made due to the personal situation of the operator. Finally, "organizational and management factors" support human error due to poor on-site organisation and management.

The **severity** of an event is assessed according to the European Scale of Industrial Accidents^{17,18} which is based on the Seveso directive¹⁷. It is used to classify the severity according to physical, human and social, as well as economic consequences:

- Q1: quantity of hydrogen released
- Q2: quantity of hydrogen taking part in the explosion
- H3: number of fatalities
- H4: number of injured persons with hospitalisation > 24h
- H5: number of slightly injured persons with hospitalisation < 24h
- €15: economical damage on-site
- €16: economical production losses on-site
- €17: external damage and production losses
- €18: rehabilitation of the environment

Because information about events is often incomplete or not detailed enough, it is often impossible to classify the severity of some of these categories correctly, or it can only be deduced with expert knowledge.

The **lessons learned** of an event are derived based on the identification of violated safety principles. In 2019, the EHSP published a guidance document for "Safety Planning for Hydrogen

¹⁷ [European scale of industrial accidents - La référence du retour d'expérience sur accidents technologiques](#)

¹⁸ [IMPEL_2013_En.pdf](#)

and Fuel Cell Projects”¹⁹, in which safety principles were extracted from the actions required to prevent an escalation of a prototypical hydrogen accident. These Safety Principles (SP), as listed in Table 2.2, formulate simple objectives, widely that are generally understandable and serve as preventive barriers or, at the very least, as risk-mitigating measures for the various elements of the chain of events.

Table 2.2. The Safety Principles (SP) of the EHSP.

Number	Safety Principle	Explosion/ Protection Tier
0	Proper design and material selection for hydrogen applications.	
1	Limit hydrogen inventories, especially indoors, to what is strictly necessary	1 st Tier
2	Avoid or limit formation of flammable mixture by applying appropriate ventilation systems, for instance	
3	Carry out ATEX zoning analysis	
4	Combine hydrogen leak or fire detection and countermeasures	2 nd Tier
5	Avoid ignition sources using proper materials or installations in the different ATEX zones, remove electrical systems or provide electrical grounding, etc.	
6	Avoid congestion, reduce turbulence promoting flow obstacles (volumetric blockage ratio) in respective ATEX zones	3 rd Tier
7	Avoid confinement. Place storage in the free, or use large openings which are also supporting natural ventilation	
8	Provide efficient passive barriers in case of active barriers deactivation by whatever reason	
9	Train and educate staff in hydrogen safety	Organisational Safety Principles
10	Report near misses, incidents and accidents to suitable databases and include lessons learned in your safety plan	

¹⁹ https://www.fch.europa.eu/sites/default/files/Safety_Planning_for_Hydrogen_and_Fuel_Cell_Projects_Release1p31_20190705.pdf

As in the previous two exercises, two experts were assigned to the same subset of events, who first executed the assessment individually, and then compared their results to reach consensus and increase the reliability and robustness of the assessment.

3 OVERVIEW OF THE EVENTS

As shown in Figure 3.1, most of the 1220 events in HIAD occurred in the period from the year 1990 to 2019 with 210-255 events per year (the 2020s still on-going and counting). Figure 3.2 illustrates the distribution of events around the globe, reflecting the origin of the accessible databases. Compared to the last report, the fraction of North American incidents has significantly increased from 26 % to 41 %. The increased fraction of 15 % of Asian events compared to 13 % in the past is an indicator for the availability of more resources from Asia, especially from Japan, Korea and China. The largest fraction is still coming from Europe, however with 42 % only slightly higher than the North American fraction. While European incidents used to populate almost 60 % of the database in the last edition, this demonstrates the successful expansion of HIAD to events across the world.

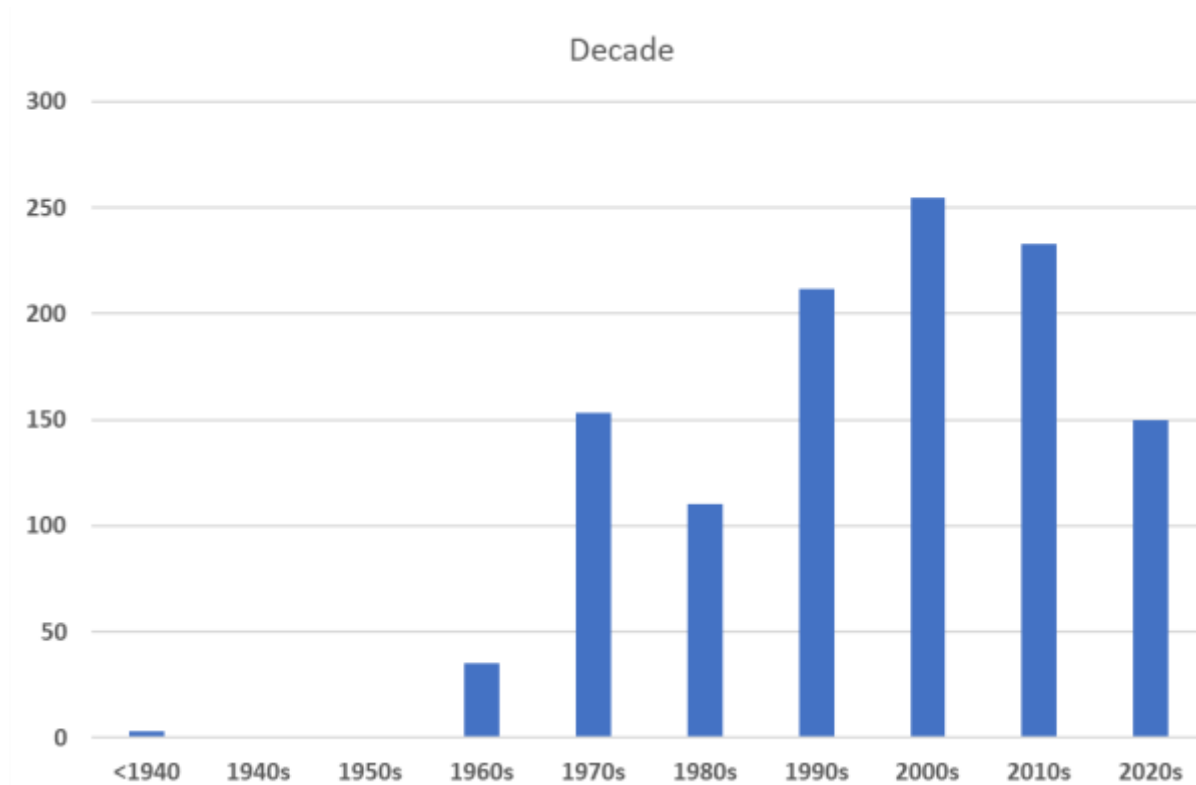


Figure 3.1. Number of HIAD events per decade (2020s still on-going and counting).

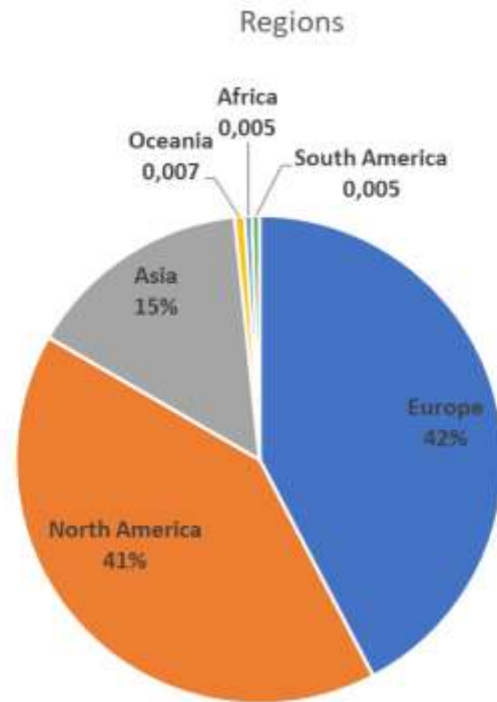


Figure 3.2. Share of different regions of the world in the database.

Events are grouped in the following three fundamental sub-categories:

- Hydrogen system initiating event: event triggered directly by the system containing hydrogen (e.g. rupture of hydrogen pipe or tank)
- Non-hydrogen system initiating event: event not directly caused by the hydrogen system but involving hydrogen (e.g. damage to hydrogen installations or vehicles caused by failure of conventional components)
- Events initiated by a system containing also hydrogen (e.g. explosion of a mixture of hydrogen and hydrocarbons or resulting from chemical reactions producing hydrogen)

Figure 3.3 shows that two thirds of the events were initiated by the hydrogen system itself, while approx. one quarter of the events were initiated by a non-hydrogen system.

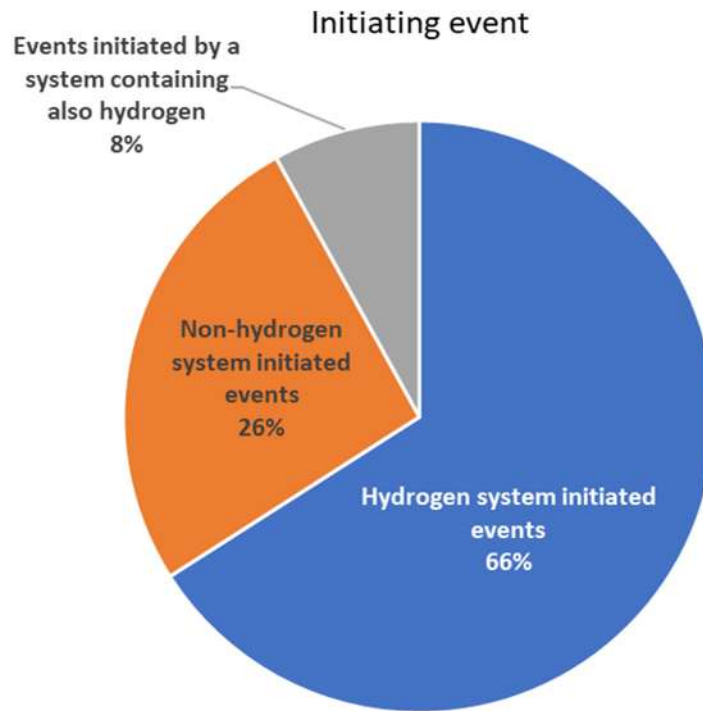


Figure 3.3. Event classification according to the initiation of the incident.

The second main classification considers the physical effects and has been expanded by JRC in recent years. In addition to the four sub-categories “explosion”, “fire”, “unignited hydrogen release” and “near miss” (i.e. no hydrogen release), new categories are “explosion followed by a fire”, “fire followed by an explosion” and “false alarm”. As hydrogen has a wide flammability range (4-76 % by volume) and requires little energy to ignite, accidentally released hydrogen is prone to be ignited in the presence of an ignition source. Hence, only 23 % of the events included in this assessment with a hydrogen release didn’t ignite (Figure 3.4).

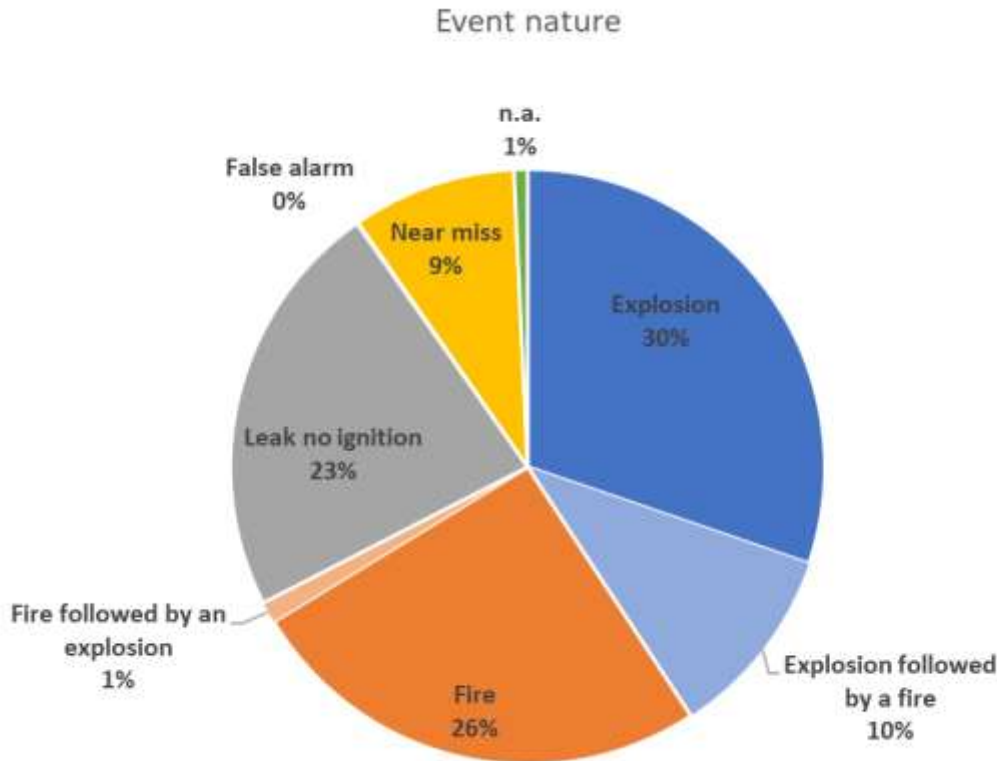


Figure 3.4. Distribution of events according to physical effects.

In the following, the statistics of the event nature are related to the event initiation (see Figure 3.5). For the sake of readability, "explosion", "explosion followed by fire" and "fire followed by explosion" were combined. The graph shows again the dominance of ignited hydrogen releases. The incidents without ignition can be attributed to various reasons, e.g. the unintended releases being promptly stopped, adequate control of the inventory and ignition sources, etc. The near misses indicate that early detection and prompt action to mitigate any potential releases can still avoid major hydrogen releases. One should also bear in mind that more cases involving unignited releases must have occurred in practice as near misses and unignited releases may often be neither detected nor reported.

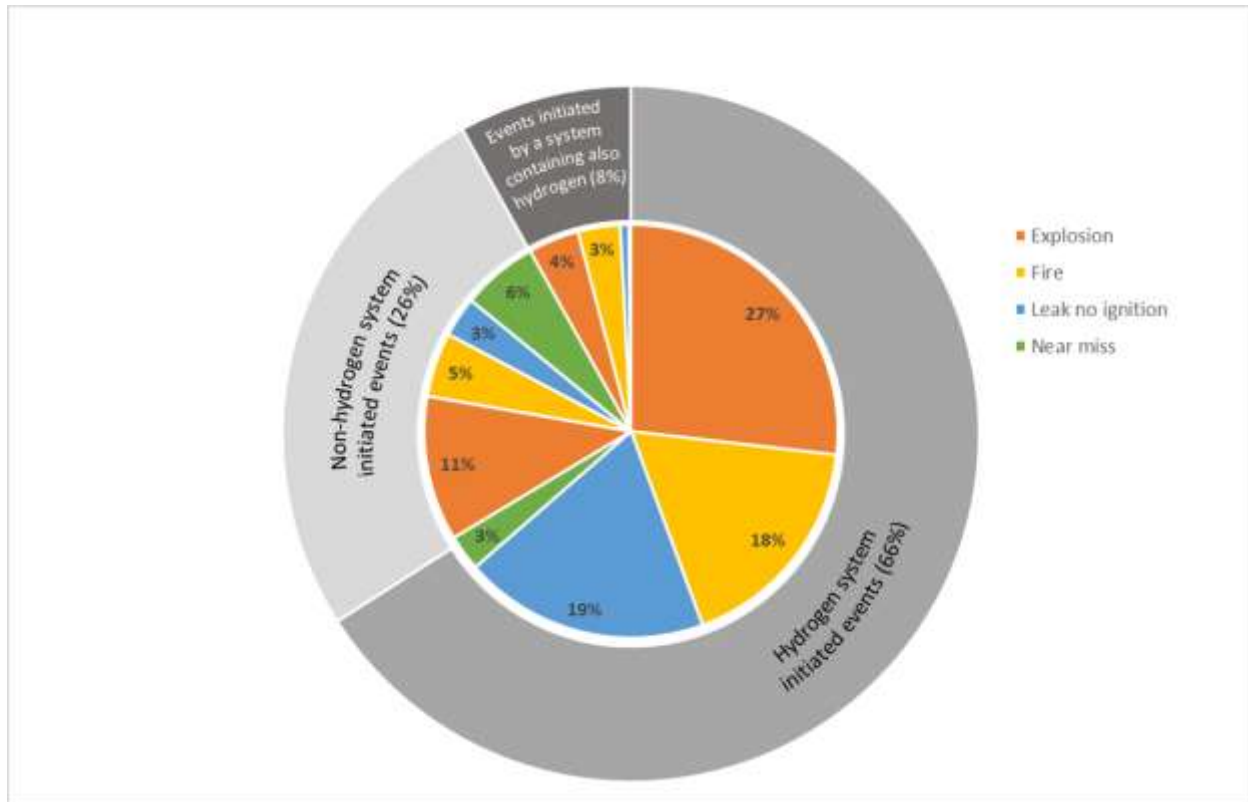


Figure 3.5. Distribution of events according to event nature.

The third main category is the industrial sector where the incident occurred. It contains several sub-categories such as hydrogen production, hydrogen transport and distribution, hydrogen refuelling station and road vehicles, etc. Figure 3.6 illustrates the percentage of events that occurred in different industrial sectors. Among the different sectors, the chemical industry and hydrogen transport and distribution have by far the largest share of the incidents with 24 % each. It is followed by the petrochemical industry with 17 % and power plants with 8 %. The other sectors under consideration account for smaller shares.

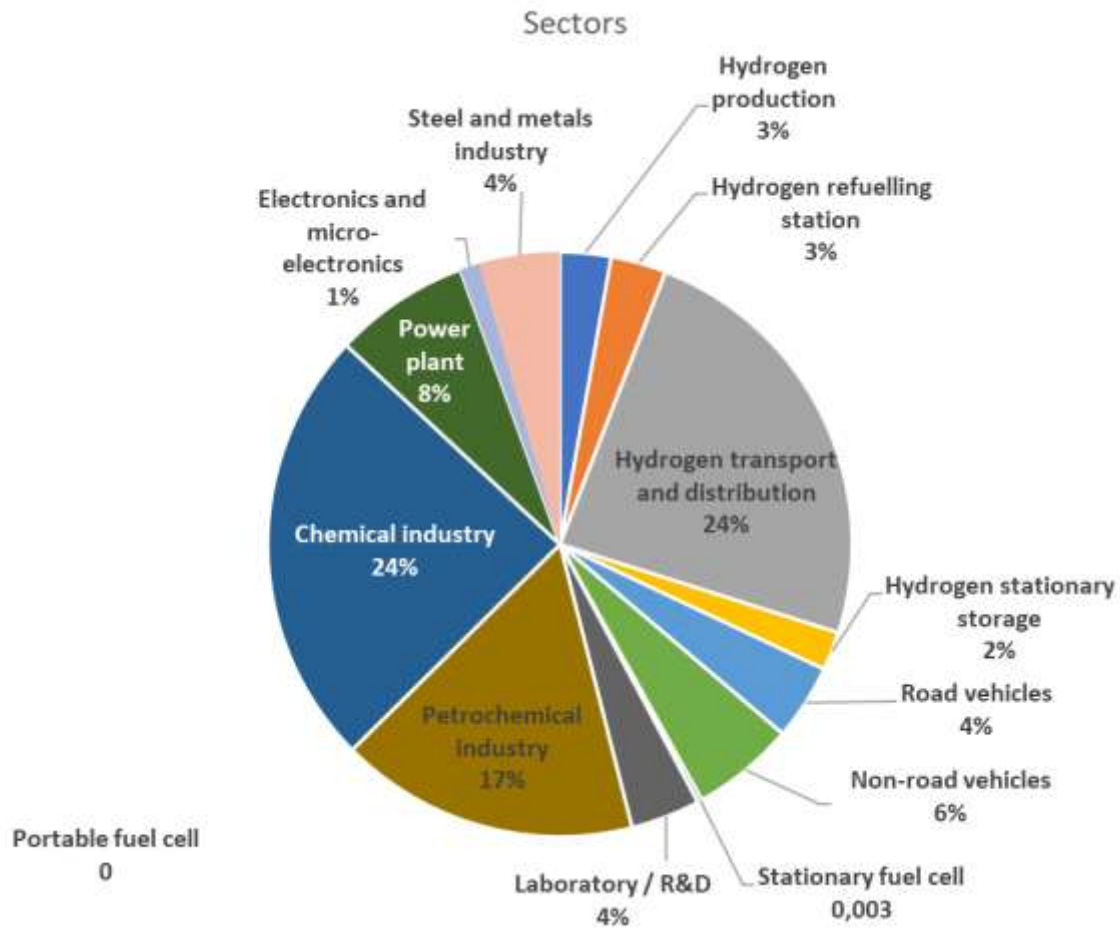


Figure 3.6. Fractions of different industrial sectors in the HIAD events.

4 STATISTICS

The analysis has comprehensively covered statistics, lessons learnt and recommendations. It is based on 898 assessed events out of the 1220 events which were in the database in March 2026.

4.1 Statistics on causes and operational mode

Table 4.1 gives the number of events related to the different causes while Figure 4.1 provides the corresponding percentage values. Some events had multiple causes and hence counted more than once.

Table 4.1. HIAD events classified by causes (multiple causes per event considered).

Cause	Number of events by causes
System design error	324
Material/ manufacturing error	271
Installation error	118
Job factors	149
Individual/ human factors	205
Organization and management factors	435

It is important to note that for almost 50 % of the events, organization and management factors were identified as one of the key responsible factors. There are 595 events for which the root causes are related to system design errors and material/manufacturing errors. 149 events are related to job factors, and the causes of 205 events were traced back to individual and human factors. Only 118 events are related to installation errors. Overall, it can be concluded that the so-called soft factors play just as big a role in the causes of incidents as technical factors related to equipment and components.

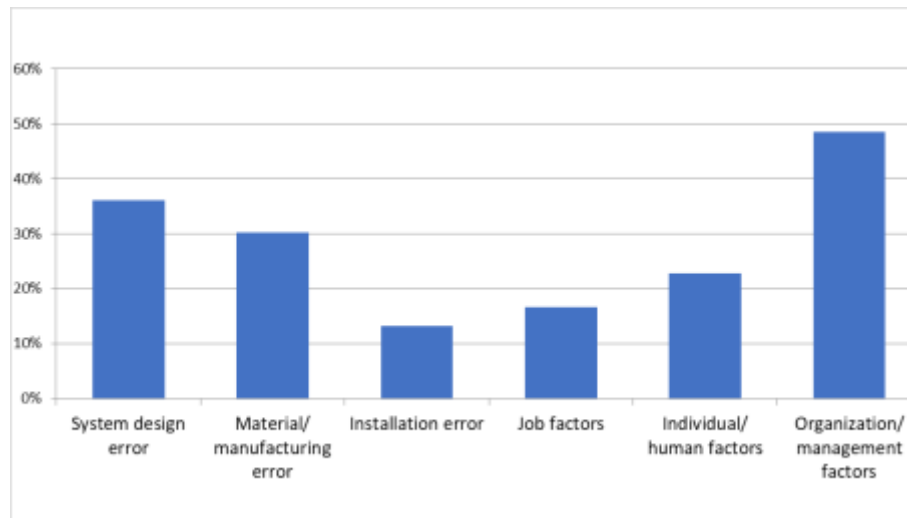


Figure 4.1. Percentages of causes of the events (multiple causes per event considered).

Figure 4.2 shows the statistics about the operational conditions at the event initiation. While the majority of 64 % incidents occurred during normal operation, 26 % occurred outside normal operation, e.g. during maintenance, repair or immediately after returning from maintenance to normal routine operation (10 % unknown). However, considering that technical systems are most of the time in normal operation, the importance of thorough risk assessment for exceptional operational situations and conditions becomes obvious.

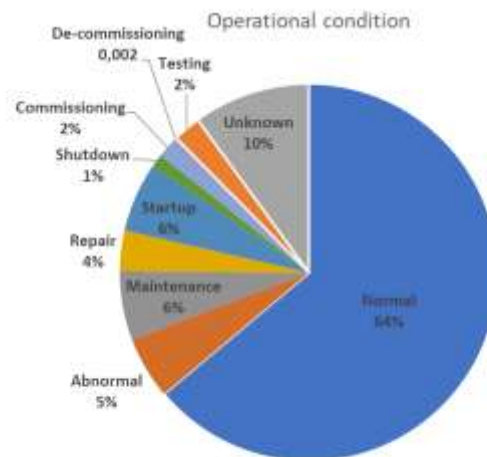


Figure 4.2. Fractions of operational modes at incident initiation.

4.1.1 Statistics on Severity

The classification of the quantity of hydrogen released in an incident (Q1) has been based on the upper threshold with a value of 50 t (see Table 4.2). This is based on the assumption of the equivalent TNT method. It should be noted that the TNT method is not a very representative method for hydrogen explosion and tends to overestimate the consequence.

Table 4.2. Classification of released amount of hydrogen (Q1).

Q1 - Quantity Q of substance actually lost or released in relation to Seveso 3						
1	2	3	4	5	6	
0,05	0,5	5	50	500		t H ₂
50	500	5000	50000	500000		kg H ₂
556	5562	55617	556174	5561735		n-m ³ H ₂

Figure 4.3 shows the fractions of the different release quantity classes. In the majority of the events (i.e., 77 %), the quantity of hydrogen released in not reported. Most of the remaining events had releases of the lowest class (Q1-1), i.e. < 556 n-m³. The maximum releases reported were assigned to class Q1-4, i.e. up to 556,174 n-m³. For 20 % of the events there was no hydrogen release.

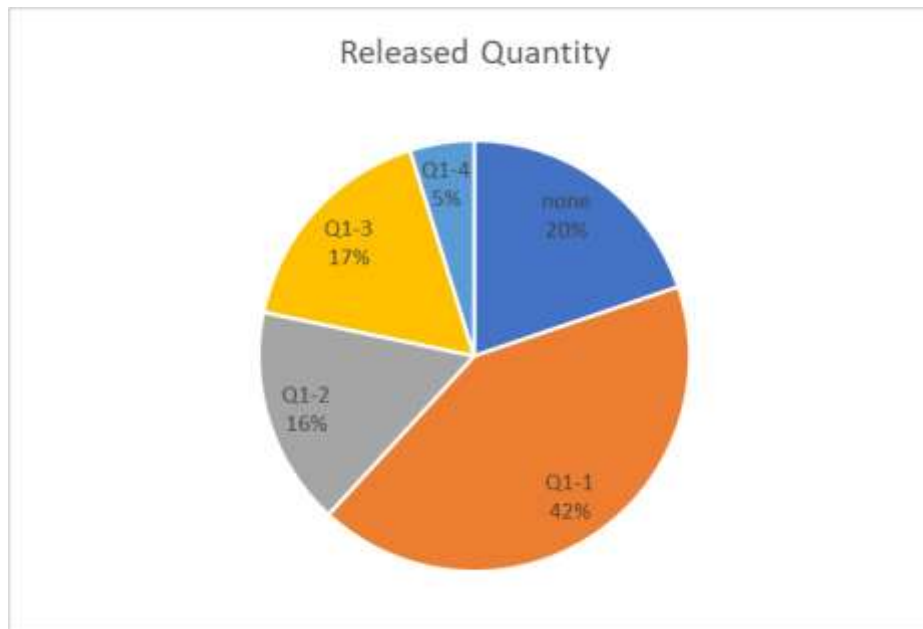


Figure 4.3. Events classified by the quantity of hydrogen releases (77 % unknown).

Information for the quantification of the exploded amount of hydrogen (Q2) according to Table 4.3 is even more sparse than for the hydrogen release (Q1). Only 11.4 % of the events involving an explosion provide sufficient information to quantify the explosion.

Table 4.3. Classification of exploded amount of hydrogen (Q2).

Q2 - Quantity Q of explosive substances having actually participated in the explosion						
1	2	3	4	5	6	
0,1	1	5	50	500		t TNT
0,0038	0,0385	0,192	1,92	19,2		t H2
3,8	38	192	1923	19231		kg H2
43	428	2139	21391	213913		n-m ³ H2

Figure 4.4 shows the corresponding class distribution. Most of the quantified events fall in the lowest class (< 43 n-m³ hydrogen exploded). Higher classes have consecutively decreasing fractions.

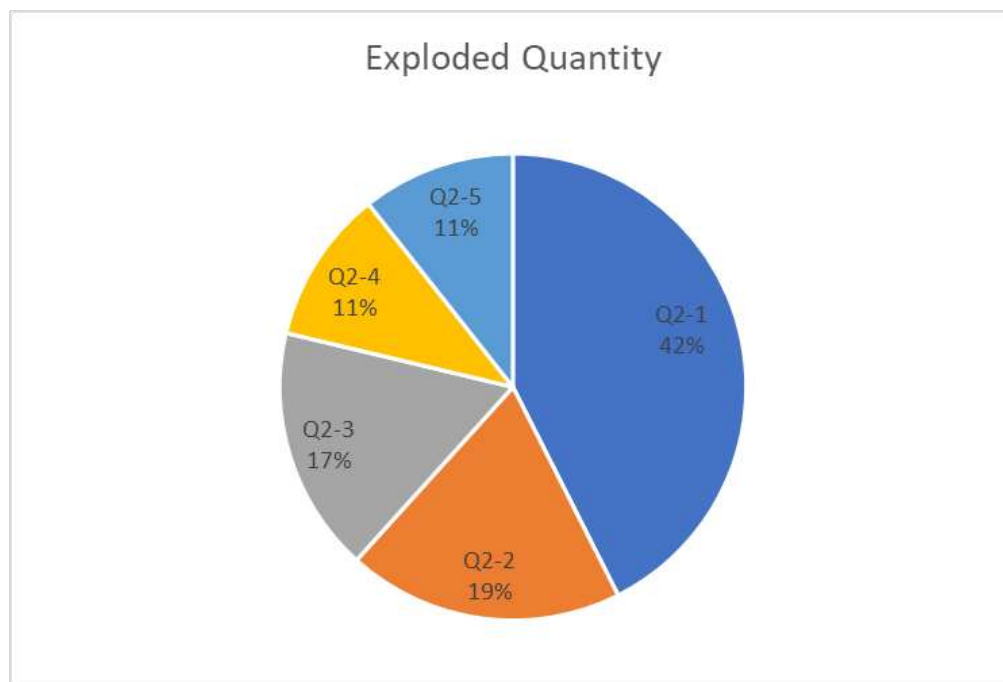


Figure 4.4. Events classified by the quantity of hydrogen exploded (89 % unknown).

For the classification of human and social consequences, the number of fatalities (H3) and injured (major (H4) or minor (H5)) persons has been identified. See 4.

Table 4.5. Classification of human and social consequences (H3 to H5).

H3 - Total number of deaths						
1	2	3	4	5	6	
-	1	2 - 5	6 - 19	20 - 49	≥ 50	total number including
-	1	2 - 5	6 - 19	20 - 49	≥ 50	- employees
-	-	1	2 - 5	6 - 19	≥ 20	- external rescue personnel
-	-	-	1	2 - 5	≥ 6	- persons of the public
H4 - Total number of injured with hospitalisation > 24 h						
1	2	3	4	5	6	
1	2 - 5	6 - 19	20 - 49	50 - 199	≥ 200	total number including
1	2 - 5	6 - 19	20 - 49	50 - 199	≥ 200	- employees
1	2 - 5	6 - 19	20 - 49	50 - 199	≥ 200	- external rescue personnel
-	-	1 - 5	6 - 19	20 - 49	≥ 50	- persons of the public
H5 - Total number of slightly injured cared for on site or with hospitalisation < 24 h						
1	2	3	4	5	6	
1 - 5	6 - 19	20 - 49	50 - 199	200 - 999	≥ 1000	total number including
1 - 5	6 - 19	20 - 49	50 - 199	200 - 999	≥ 1000	- employees
1 - 5	6 - 19	20 - 49	50 - 199	200 - 999	≥ 1000	- external rescue personnel
-	1 - 5	6 - 19	20 - 49	50 - 199	≥ 200	- persons of the public

In between 15 and 18 % of the events the classes couldn't be allocated due to lack of information. For the remaining events, Figure 4.5 shows that 87 % did not lead to any fatality (H3-1). Some major accidents, e.g. events IDs10, 21, 611, 695 and 698, led to more than 20 deaths each. Most of the fatalities in these incidents were caused by the explosion of a hydrogen-air gas cloud. Statistics on injured persons and hospitalisation are given in Figure 4.6 and Figure 4.7.

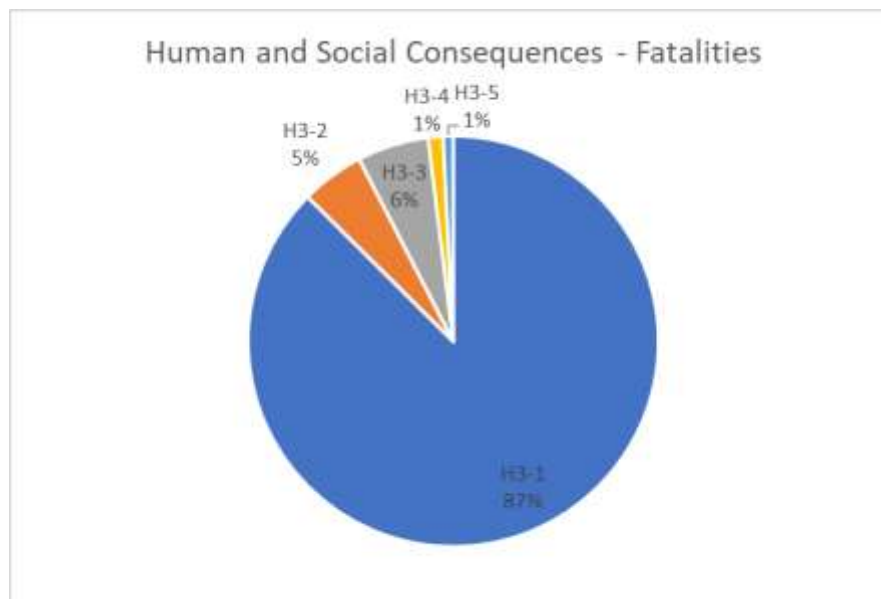


Figure 4.5. Statistics on fatalities (15 % unknown).

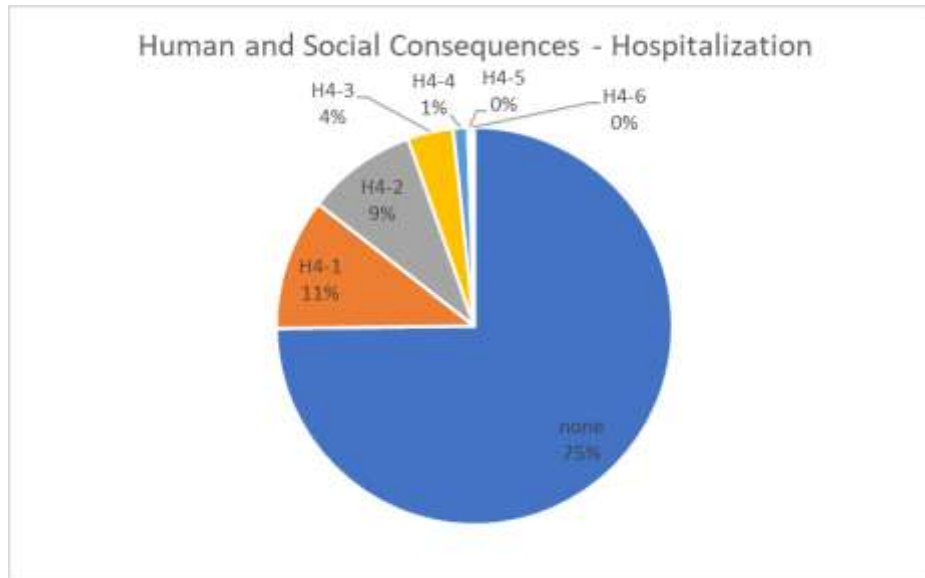


Figure 4.6. Statistics on significantly injured persons (16 % unknown).

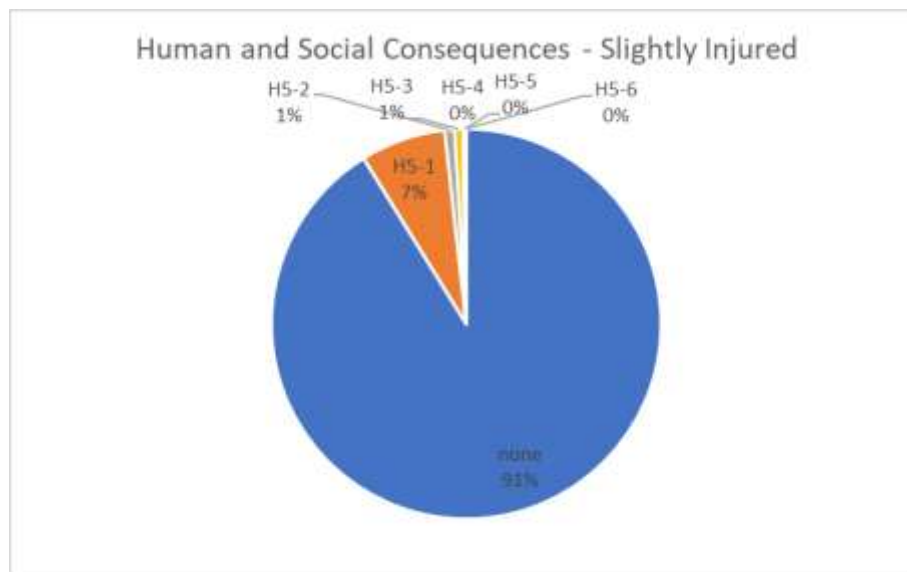


Figure 4.7. Statistics on minor injuries (82 % unknown).

Among the factors that characterize the severity of an incident, data on financial losses (Table 4.6) are the most difficult to assess, as concrete information is available only in the rarest of cases. Detailed statistics on this are therefore not meaningful. However, it can generally be stated that internal damage occurred in 80% of incidents (Figure 4.8), while internal operational losses occurred in 83 % of incidents (Figure 4.10). In 24 % of cases, property damage also extended to external facilities and the surrounding environment (Figure 4.9).

Table 4.6. Classification of economic consequences (€15 - €18).

€ - Economic consequences in Mio. €							
	1	2	3	4	5	6	
€ 15	0.1 - 0.5	0.5 - 2	2 - 10	10 - 50	50 - 200	≥ 200	Damage on-site
€ 16	0.1 - 0.5	0.5 - 2	2 - 10	10 - 50	50 - 200	≥ 200	Production loss on-site
€ 17	-	0.05 - 0.1	0.1 - 0.5	0.5 - 2	2 - 10	≥ 10	Damage/Prod.losses off-site
€ 18	0.01 - 0.05	0.05 - 0.2	0.2 - 1	1 - 5	5 - 20	≥ 20	Rehabilitation environment

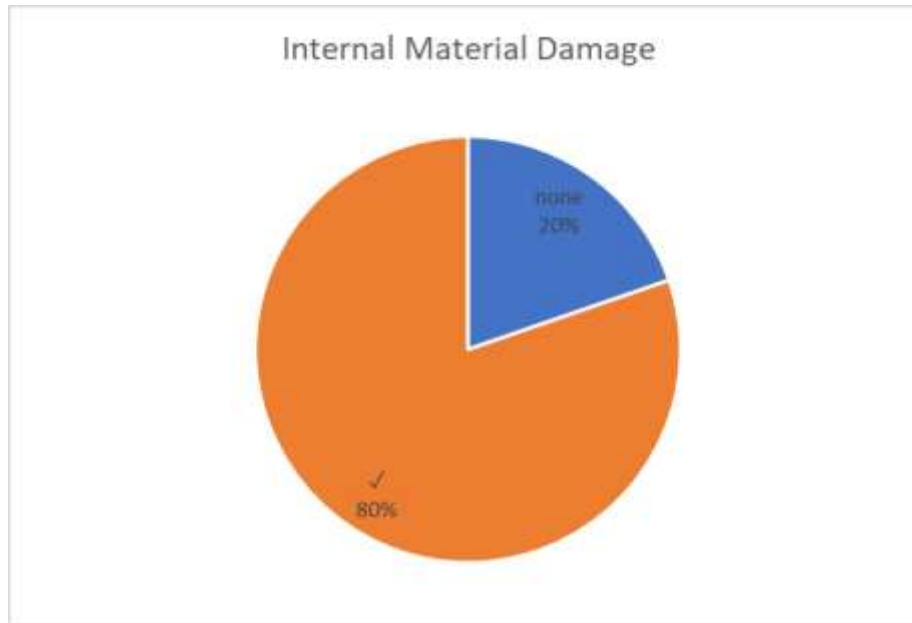


Figure 4.8. Fraction of events with internal material damage (25 % unknown).

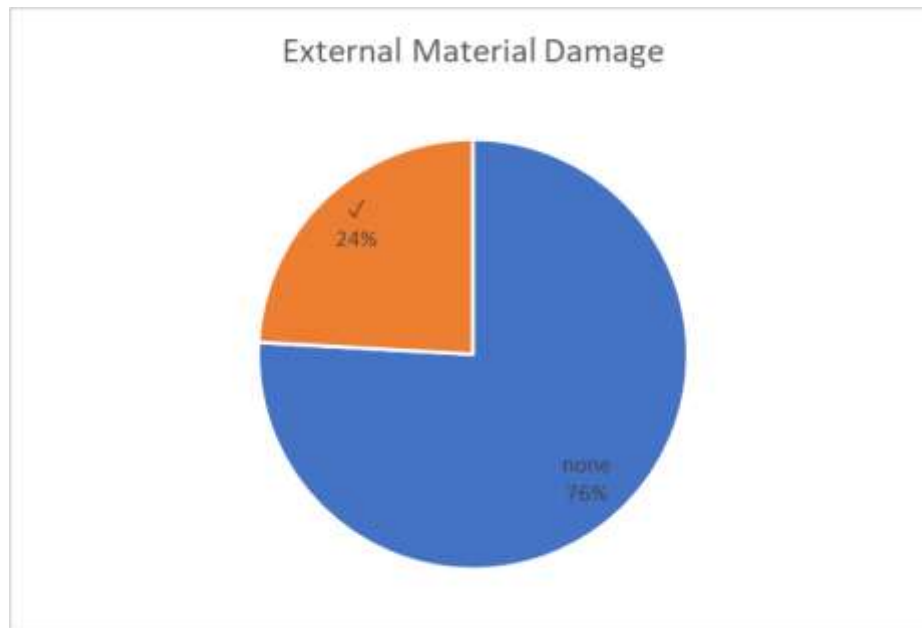


Figure 4.9. Fractions of events with external material damage (46 % unknown).

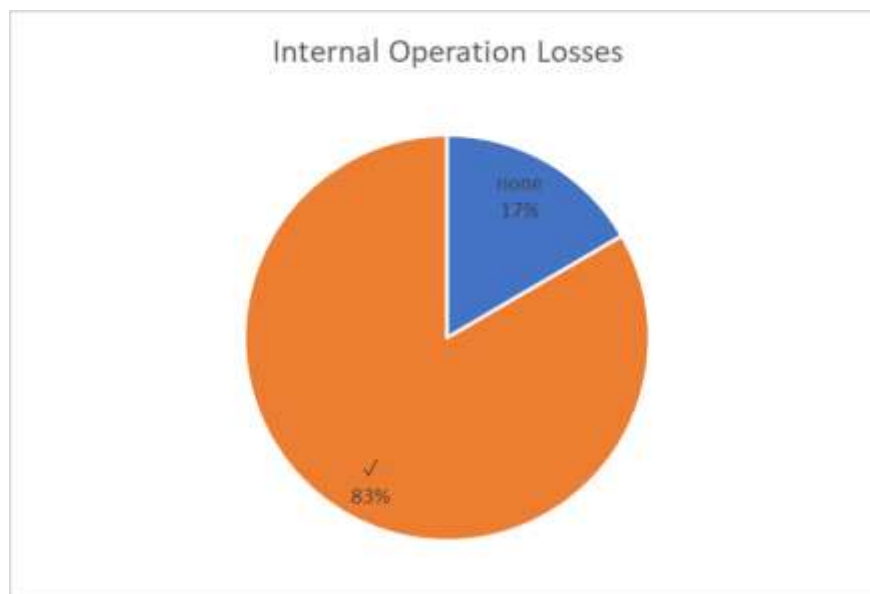


Figure 4.10. Fractions of events with internal operation losses (32 % unknown).

4.1.2 Statistics on Violated Safety Principles

The statistics on violated safety principles are shown in Figure 4.11. The major contributing factors are SP9 (53 %) and SP0 (51 %), multiple entries possible. These results indicate that lack of training of operators/plant personnel and lack of understanding of hydrogen hazards in the plant design are key areas which need further improvement. In addition, reporting incidents and

near misses and applying consequences from past events in the safety planning (SP10) is another major aspect which should have been considered in a significant share of incidents.

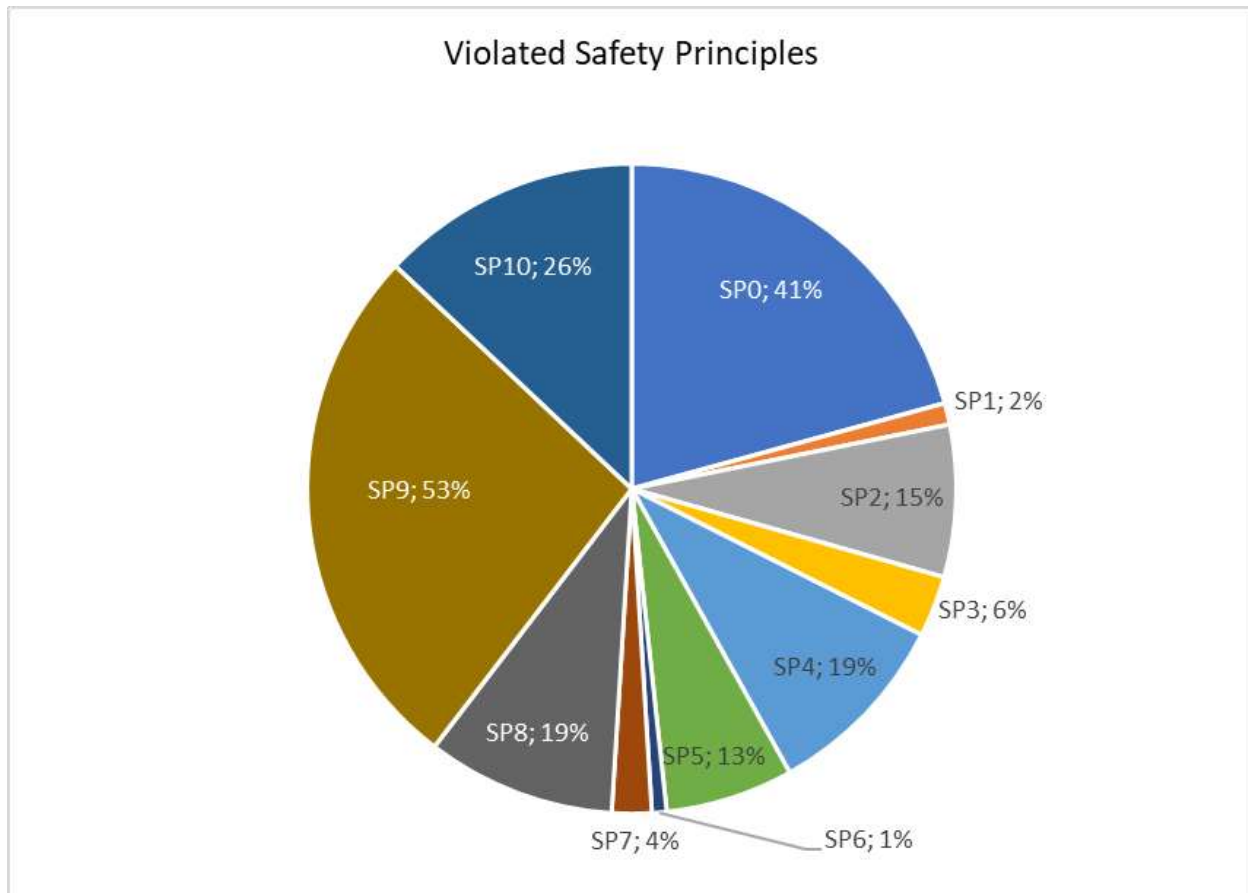


Figure 4.11. Violated safety principles listed in Table 2.2(multiple entries possible).

5 LESSONS LEARNT

EHSP Task Force TF3 has further analysed 898 events out of the 1220 events which are in HIAD as of May 2026. Due to the limited time available, it was decided to leave the remaining events to be analysed next year together with any new events that are continuously being added to HIAD. As introduced earlier, the statistics in Chapter 4 included the events considered in our previous report² as well as 305 newly added/validated events since then. As described in Chapter 2, JRC has significantly expanded HIAD new events over the past three years and distilled lessons learnt from their analysis. For completeness, this Chapter has kept the contents of the “lessons learnt” in our previous report² with some minor amendments quoting examples from the newly added events. A new section has been added, focusing on lessons which can be learnt from the newly added LH2 events that were formulated by JRC. Table 5.1 has, hence, been modified accordingly to include this category.

Table 5.1 . Categories and sub-categories used in lessons learnt analysis

Categories	System design	System manufacturing, installation and modification	Operator errors			First responders
			Job factors	Individual/ human factors	Organization& management factors	
Sub-categories	Design related	Material compatibility	Maintenance and inspection	Bypassing key interventions	Out of date inspection plan	Insight of H2 safety and accident scenarios
	Corrosion related	Venting system	Safety device during maintenance	Inadequate training of H2 truck drivers	Inspection of safety equipment	Delay in limit inventories
	Fatigue	Weak points	Safety practice and procedures	Monitoring pressure of the filter	Procedures for plant modification	Training
	Pressure relief valve	System installation	Lack of clear instructions	Irregular purging of the system	Safety supervision during repairing work	Emergency response inhibited by poor drainage
	Equipment factor		Chemical compounds prone to H2 generation	Verification of design and operation conditions	Procedures for fast isolation of the release sources	Lack of sufficient evidence gathering
	H2 generation due to malfunction		Insufficient check after repair	Emergency procedure not followed	Guidance about lifetime of critical components	Extinguishing fire before H2 release stopping

	Venting		Insufficient purging Before re-using	Guidance to prevent unwanted H2 generation	Explosivity control before maintenance	Efficient safety crew
	H2 accumulation			Handover between shift and day staff	Distinction between emergency and operating alarms	
	2 nd order redundancy on critical systems			Ignorance about volatile pressure of hydrocarbons in tanks		
				workplace safety violation		
	LH2 Systems					

5.1 Lessons learnt related to system design

Some design issues were identified as the causes of numerous incidents. In the following, these are grouped according to the sub-categories which were identified as being most relevant. It should, however, be recognised that many incidents were caused by multiple malfunctions. Wherever appropriate, this aspect is mentioned in the description.

5.1.1 Design related

An important lesson is to ensure inherently safety design. Some incidents were caused by design problem. For example, the explosion in event ID687 was caused by the release of about 30 kg of hydrogen gas into a compressor shed from a burst flange operating at about 47 bar after the unit was being restarted following a regular semi-annual turnaround. Although the specific design issues which might have caused the incident were not identified, the operator decided to carry out plant modifications to prevent recurrences of similar incidents. Incident ID1056 highlights a case of erosion affecting a poorly designed component (a Coriolis flowmeter) that was not subject to regular inspections on a hydrogen transport pipeline, which led to a leak and a fire. Incident ID1085 reports a leak from a vent connection on a booster following the use of that booster with an H2/CH4 blend for which it was not designed. Event ID1131 highlights a design issue in the BOP of an electrolyser, specifically the presence of a tank in which effluents

containing dissolved oxygen and hydrogen are stored simultaneously, leading to the formation and explosion of an ATEX atmosphere within the gas phase.

Lack of precaution during the design stage to limit hydrogen inventory, place the inventory outside and protect vessels against thermal attacks, etc., were all found to result in some incidents. For example, event ID734 was partially caused by lack of clear separation of combustible gas from the oxidizer and ignition source; event ID542 was traced back to piping system leaks which could have been avoided by welding the piping system with the exception of flanged joints.

Some incidents were caused by a combination of design issues and human error, e.g. event ID179, in which hydrogen was accidentally released during the filling of a 28 bottles rack. It was found that the feeding pipe was still connected to the rack in the process and resulted in the rupture of the pipe to cause hydrogen leak. The design of the connection between the stand and the bottles was not sufficiently visible. As a result, when the operator removed the rack, he could not see that the feeding pipe was still connected. Inherently safe design could have helped to render the key connections to be clearly visible and hence less likely to be damaged by human errors. Incident ID1040 involved a road traffic accident involving a tube trailer. The safety systems functioned correctly, but ruptures caused by the crash resulted in horizontal jet flames. Such flames can pose a serious hazard in a populated area and must be prevented by design. Event ID1089 highlighted a design issue combined with human error. During a hydrogen delivery, the operator connected to the air supply rather than the hydrogen supply, causing an ATEX hazard and an explosion in that circuit. The connections looked similar and were not clearly labelled. There was no cross-checking, and the risk assessment was seriously at fault for failing to identify this weakness.

Lack of due consideration for extreme weather conditions could also result in incidents. For example, icing could result in blockage and cause over pressurization in some systems. In event ID552, the blockage resulted in fracture of the second stage cylinder of a hydrogen compressor. Heavy rains could lead to water accumulation, e.g. the explosion event ID558 which occurred during the cleaning of a blast furnace was caused by accidentally generated hydrogen due to dissociation of the accumulated water after hot slag and was poured into a pit. Lack of consideration during design stage for adequate protection against extreme weather incidents such as lightning and heavy rains could trigger initiating incidents such as thermal stresses on pipes, e.g. event ID572.

5.1.2 Corrosion related

Considerable number of incidents were found to be related to corrosion, the occurrence of which was not detected through regular inspection, prevented from maintenance, or lack of due consideration of the hydrogen compatibility of materials used. For example, event ID95 was caused by the corrosion of heat exchanger. Other incidents caused by corrosion include events IDs: 83, 104, 122, 131, 179, 194, 196, 208, 210, 246, 261, 478, 546, 567, 568, 615, 616, 648, 707. Event ID620 was by high temperature hydrogen attack and ID568 was related to dead leg (section of process piping that has been isolated and no longer maintain a flow of liquid or gas) corrosion by ammonium chloride. Regular inspection and maintenance could have helped to prevent corrosion related incident.

5.1.3 Fatigue

The fatigue of components resulted in partial loss of mechanical integrity in some incidents, e.g. event ID498, which involved a violent explosion in a factory manufacturing nitrogen fertilizer was suspected to be related to possible failure of welded components due to fatigue. A series of incidents were caused by lack of periodic verification/audit of the structural integrity of the hydrogen tank. This is an important lesson to learn.

5.1.4 Pressure relief valves

Some incidents indicated inadequate design and/ or installation of pressure relief valves in the pressure systems, e.g. event ID808. Another example is event ID562, which was caused by the absence of a pressure relief valve at the recycle compressor's injection point upstream of the isolation valve and failure to operate the system valves in the correct sequence. Appropriate design and installation of pressure relief valves could help prevent such incidents.

5.1.5 Equipment factor

The explosion and fire in event ID609 were due to reverse flow in the raw material tank caused by excessive opening of the valve, which was suspected to be related to maintenance issues or inappropriate materials. Equipment factor and poor apparatus was also mentioned in event ID612 involving two workers being injured when an explosion and fire occurred at a plant during shutdown operations for routine maintenance. Similarly, these factors were also mentioned in event ID613. Regular maintenance of the equipment could help preventing such incidents.

5.1.6 Hydrogen generation due to malfunction

In event ID522, hydrogen explosion in the core spray system at the Brunsbüttel BWR in Germany was traced back to the design which was vulnerable to hydrogen generation due to water splitting by the neutron radiation from the reactor core. Event ID492 in a nuclear power plant was caused by the formation of hydrogen by radiolysis of reactor water in a core, which exploded and possibly transited to detonation in the pipe. The explosion in event ID510, which was related to the cleaning agent indicated that chemical decomposition of the heavy alcohol component could release hydrogen at temperatures much lower than previously assumed. Event ID 525 was also caused by accidentally generated hydrogen while event ID 514 was linked to a ruptured seal on a valve in the blast furnace gas pipework caused the release. Robust design to prevent/ limit accidental generation and awareness of potential scenarios/ agents which could result in hydrogen generation could help to prevent such incidents from occurring.

5.1.7 Venting

Some incidents were caused by the lack of provision for safe venting of hydrogen. Several incidents were related to inappropriate ventilation and detection system as well as the later not directly linked to an automatic alarm, e.g. a temperature controller on the pipe directly connected to an emergency shut down. For example, event ID670 was caused by inadequate ventilation of the stack base space and the lack of equipment installed to monitor explosive gas concentrations within the enclosure; event ID674 was suspected was partly due to the ventilation system had not been activated; and in event ID680, the cylinders were stored indoor without adequate ventilation and detection system. Appropriate provision for ventilation and safe siting of the vents could have helped to prevent the build up of the leaked hydrogen and direct any leaked hydrogen away from the enclosure to avoid reaching the ignition source.

5.1.8 Hydrogen accumulation in confined/semi-confined spaces

Several lessons can be learnt from incidents caused by hydrogen accumulation in confined/ semi-confined spaces:

- Explosive mixture with hydrogen in stagnant zone of pipe systems could result in incidents such as those in event IDs 533 and 571. Both were related to radiolytic gases in nuclear power plants.
- Internal pump might create vacuum inside tanks with possible air ingress to form an explosive atmosphere, e.g. event ID551.

- Dead legs, which are sections of process piping that have been isolated and no longer maintain a flow of liquid or gas, were identified as weak points in event ID568.
- Pipe trench with hydrogen pipes near other hot pipes is a potential hazard, e.g. it was the cause of event ID544. In such situation, clear separation distance could have prevented such incidents and also made it easier for access by the emergency services.
- In some incidents, the production or leakage of hydrogen occurred in conjunction with an increase in temperature. However, thermocouples installed to monitor temperature changes are often installed outside the pipes and cannot react fast enough. The installation of some temperature sensors as close as possible to the gas flow could have raised early alarms to help isolate the source in events IDs 650, 655, 656 and 657.
- In some other incidents, mounting hydrogen cylinders vertically upwards could have prevented ignition of the accidentally released hydrogen, e.g. event ID719.

5.1.9 Second-order redundancy on critical systems

Provision of second-order redundancy in some hydrogen facilities could have prevented some incidents, e.g. for event ID553 which involved incorrectly calibrated transmitters, secondary stops fitted to key controllers/ valves could have limited the gas flows due to malfunction (ID553).

5.1.10 Highlighted events with important lessons to be learnt related to system design

In event ID499, two hydrogen explosions occurred at the Millstone Nuclear Power Station Unit No. 1. The accumulation of explosive hydrogen mixtures was considered in the design of the BWR offgas system. As a result, the design had prevented major releases of airborne radioactivity in the approximately 25 known hydrogen gas explosions that occurred within the offgas systems of operating BWRs prior to this incident. In addition to uncontrolled release of radioactive material, hydrogen accumulation outside of the offgas system led to five explosions including this one, resulting in extensive mechanical damage to the equipment and structures. It was found that the action taken to restore offgas system drain line loop seals in the stack base space had not been successful. Without these seals, gases from the offgas system accumulated in the space, resulting in an explosive mixture which was probably ignited by a spark from the level switch in the stack base sump. Inadequate ventilation of the stack base space and the lack of equipment installed to monitor explosive gas concentrations within the enclosed area were concluded to be contributing factors.

Event ID526 involved a serious chemical accident in a petrochemical company, which resulted in injuries to several workers and extensive damage to the plant, as well as minor damage to nearby residential property. Damage to the facility was estimated at \$101 million and major transportation routes were closed for several hours. The incident was traced back to internal structural failure and drive shaft blow-out of a 36-inch diameter check valve. The check valve's failure resulted in a large flammable gas leak, forming a vapor cloud that ignited. Fractography revealed typical hydrogen embrittlement damage. Explosion energy calculation assessed the hydrogen content in the vapour cloud to be around 20%. The EPA/OHSA Shell report of 1998 identified the following design issues:

- Inadequate valve design.
- Failure to learn from prior incidents.
- Inadequate process hazards analysis.
- Inadequate mechanical integrity measures, and
- Inadequate operating procedures plus the following contributing factors: no indication of hydrocarbon leak, delayed operator response to leak and inadequate communications practices.

5.2 Lessons learnt related to system manufacturing, installation and modification

System manufacturing issues were identified as the causes of numerous incidents. In the following, these are grouped according to the categories which were identified as being most relevant. It should, however, be recognised that many incidents were caused by multiple malfunctions and some system manufacturing issues were indeed also related to design. Wherever possible, the description below endeavoured to point such multiple issues out.

5.2.1 Material compatibility

Event ID534 in 1994 was the first reported of such incidents related to the use of materials incompatible with hydrogen. This incident triggered the development of the German pressure vessel code and standards. Event ID615 involving vapour cloud explosion was traced back to the crack in a storage tank releasing gaseous hydrogen to atmosphere. Use of materials compatible with hydrogen would help to prevent such incidents. Periodic audit and maintenance, on the other

hand, could help to detect any defect promptly to ensure timely attention. For those concerned, general information about material compatibility can be found in reference²⁰.

5.2.2 Venting system

Hydrogen venting system malfunctioning could lead to severe consequences, e.g. in ID536, road tanker carrying 125,000 cubic feet of liquid hydrogen caught fire when the tankers vent stack malfunctioned. The area within a one-mile radius had to be evacuated. Regular inspection and maintenance could have helped to identify potential problems and trigger corrective actions to prevent such incidents.

5.2.3 Weak points

Equipment often has components or points such as joints, which are relatively weaker than other parts and vulnerable for failure. In the following, some examples of incidents caused by different types of weak points are provided to illustrate that such incidents could have been prevented if appropriate attention was given to monitor and avoid failure of these weak points or their timely replacement with new parts:

- Gauge glass for liquid tank level monitoring, which resulted in the fire incident in a refinery in ID545.
- Flange connections were flagged up in numerous incidents as weak points which are prone to leaking. In event ID672, the flanges and bolts on the outlet of the reactor were cooled down and shrank due to a large amount of rainwater penetrating to the rain-cover around the flanges. This caused the deformation and deterioration of the ring gaskets due to the extra stress induced by the over tightness, resulting in the leak of hydrogen gas and light oil mist which ignited spontaneously. Event ID1060 reported a failure of a blind flange connection.
- Event ID548 was due to the piston rod at the threaded attachment to the cross head, which then resulted in the failure of the studs of the driven end first stage cylinder head. Such failure could have been identified through regular inspection and prevented by regular maintenance.

²⁰ ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems.

- Welding was found to be the weak point in quite a few incidents. For example, event ID244 involved the impact of thermal hazards from an initial fire on the hydrogen pipe. This resulted in a weld to rupture, resulting in the leak of hydrogen, which exploded. The subsequent fire caused an electrical short-cut which set on the phenylacetyl carbinol pump, feeding the fire with flammable liquid. Event ID1057 reports a circumferential rupture in a hydrogen transport pipeline at a weld.

Awareness of such weak points through staff training and appropriate actions to protect them could help to reduce such incidents.

5.2.4 System installation

In some incidents, electrical and magnetic problems were the likely causes, e.g. electrical system including power load rejection, lack of protection against electromagnetism, and use of equipment not meeting ATEX requirement close to hydrogen tanks. Several incidents could have been prevented or intervened earlier if hydrogen sensors were installed and redundant and diverse measurement systems were used. For example, ID692 could have been avoided if appropriate detector system was installed to monitor potential hydrogen releases and automatic shut valves were installed to cut off the feed in the event of system malfunction.

The escalation of some incidents could have been prevented by the use of fire barriers to prevent further ignition and appropriate separation distances between separate hydrogen systems such that jet fire in one system cannot affect another hydrogen system.

The explosion of event ID529 involving the transportation of hydrogen balloons, which started from small leakage into the sealed bag used for their transportation, could have been prevented if mesh container was used.

Rupture disks could fail due to manufacturing or installation error, e.g. in incidents ID541 and ID687, the metallurgical problems were found on the equipment, which was not compliant with the requirements of the operator. Appropriate system installation following operator's requirement could help to reduce such incidents.

Event ID1058 describes a complex incident involving an underground hydrogen pipeline located near the earthing stake of an electricity transmission pylon. A lightning strike on the pylon is believed to have caused a localised defect in the pipeline, resulting in the leak. A proper assessment prior to installation work can help prevent this sort of incident.

5.2.5 Highlighted incident with good lessons to be learnt related to system modification

Event ID707 involved explosion in a ceramic factory of 370 kg of hydrogen, which leaked from a 100 m³ tank. The resulting pressure wave caused significant damage to exterior buildings; a fragment of the tank was found several hundred meters from the place of the explosion. A fire broke out soon after on the site and threatened storage of acetylene and hydrogen fluoride. A safety perimeter of 500 m was set up, road and rail traffic were stopped, the population evacuated. The tank had been put into service in December 1982, after having been modified to notably increase its storage capacity. Its first regulatory check after 5 years of use had revealed nothing abnormal, the second was due to take place a few months after the accident. Operating at a maximum operating pressure of 44.1 bar, the storage was replenished as soon as its pressure fell below 15 bar (several times a week). The last loading by an external company had been carried out less than 2 hours before the explosion. Fatigue corrosion was identified as the source of the leak. The modification work carried out on the tank and in particular the removal of the roof along the weld had caused the tank to be oversized and induced tension in the material. Frequent filling of the inventory only accelerated the weakening process of the tank. Regular inspection and maintenance against corrosion as well as monitoring and adequate attention on potential weak points could have helped to prevent such incident. While such practice could be better enforced through appropriate and regular staff training.

Event ID1080 relates to an incident involving a chlorine tank at a water treatment plant. The tank was originally located outdoors, but the company had built a shelter around it to protect it from external weather conditions. Without any changes to procedures or the installation of detectors, maintenance work involving a grinder led to the explosion of a flammable atmosphere present inside the enclosure.

In incident ID1084, a crossover caused by defects in the stacks on an electrolyzer led to an explosion in the oxygen vent line. These defects could not be detected by the pressure drop tests carried out during the restart following maintenance, as the thresholds had been adjusted from those originally recommended.

5.3 Lessons learnt related to operator errors

Human errors are unavoidable regardless of their skills or training. However, when handling hydrogen or any other flammable gases, the consequences of these mistakes can be severe. Sometimes, several small mistakes can combine and result in more serious incidents. As

reported in Section 4, analysis of the incidents in HIAD 2.0 indicated that human errors as well as technical errors were quite often the cause of incidents.

In the analysis for lessons learnt from past incidents related to operator errors, the classification²¹ proposed by the Health and Safety Executive (HSE) is adapted. The HSE classification divide the factors that influence the likelihood of operator errors into sub-categories. The three sub-categories that influence human performance are the job itself, the individual and the organisation. The definition of each of these sub-categories can vary in different situations and by different authors.

The following lists some examples to help illustrating how they are classified in this report:

- **Job factors:** unsuitable design of equipment and instruments, design fault, missing or unclear instructions; poorly maintained equipment; high workload; noisy and unpleasant working conditions; constant disturbances and interruptions, etc.
- **Individual/human factors:** inadequate skill and competence levels; tired staff; bored or disheartened staff and individual medical problems, etc.
- **Organisation and management factors:** poor work planning, leading to high work pressure; lack of safety systems and barriers; failure to learn from previous incidents; management too biased to one-way communications; lack of co-ordination and clear definition of responsibilities; poor management of health and safety; poor health and safety culture.

The statistics gathered from HIAD as described in Section 4 clearly indicates the importance of serious consideration about lessons to be learnt in these three categories with the aim to reduce the occurrence of all types of human errors.

5.3.1 Lessons learnt related to job factors

Most incidents reported under this sub-category were initially caused by lack of regular and appropriate maintenance and inspection. Some could also be attributed to unclear instructions. The lessons learnt related to these two most representative sub-categories are detailed below.

²¹ <https://www.hse.gov.uk/humanfactors/topics/humanfail.html>

5.3.1.1 Lack of maintenance or inspection

Considerable number of incidents could be traced back to poor or irregular maintenance. Event ID185, for example, was caused by material failure due to poor maintenance. Poor or inadequate maintenance were also found to result in malfunction of the system, which then degenerated and resulted in incident. Examples include a non-closed valve in event ID106, the use of non-hydrogen-compatible material in event ID241 and a safety barrier that was put back in the wrong position in event ID410. A jamming valve was not inspected and repaired in event ID1053 leading to hydrogen/oxygen mixing and explosion.

Some events were caused by lack of regular inspection, e.g. the explosion in event ID661 which occurred in the chlorine collection system, was attributed to flow restriction and mechanical equipment failure, which was not detected through regular inspection. Pipe failure in events IDs 194, 196 and 621; as well as bolt failure in event ID405 could have been avoided by regular inspections of these components. Similarly, event IDs101, 702, 703 and 708 were also linked to the lack of regular inspection. Regular inspection and maintenance could have helped to prevent a significant number of incidents.

5.3.1.2 Special attention for safety devices during maintenance

Components such as fittings, gaskets, flanges, valves, etc. are often identified as weak points of hydrogen systems. This aspect was also discussed in Section 5.2. Some incidents were caused by lack of special care on these components during maintenance and inspections or the lack of periodic audit on such devices. As a result, their malfunctioning led to some dramatic consequences, e.g. the fire in event ID156 and the severe explosion in ID475, which resulted from the lack of maintenance on an emergency shut-off valve of a tube trailer. Another example was the explosion in event ID559 involving a trailer transporting liquid which occurred near the discharge valve of the truck was due to hydrogen leak from the damaged valve. Similar incidents described in IDs249 and 601 involved faulty non-return valves. Incidents IDs542, 547 and 549 indicated that some preliminary tests at lower pressure and temperature would probably have identified weak points during maintenance involving gaskets, flanges and welded parts in hydrogen systems. Another example is event ID678, which was caused by the negligence of the regular inspection of the gasket retainer and lock ring and their appropriate maintenance. These incidents indicated that special attention for weak points can improve their safety and prevent accidents.

5.3.1.3 Training and enforcement of safety practice and procedures

In event ID 679, the pipe was incorrectly installed, this led to shutdown valves failed to operate. Some incidents were caused by the lack of compliance with company procedure, e.g. in event ID 675, the compressor manufacturer did not comply with the company's practice for reciprocating compressors in H₂S applications. Appropriate training and enforcement of compliance with safety practice and appropriate procedures can help to reduce incidents due to individual/ human factors.

5.3.1.4 Lack of clear instructions

Some incidents were caused by lack of adequate process instructions or such instructions were not readily available. For example, event ID 321, which involved the motor of the vacuum cleaner acted as an ignition source to some accumulated combustible gases in an unnamed process, was because the employer did not observe the concentration change in the system and verify that system purging was complete before using a vacuum cleaner. The vacuum cleaner being not a special ATEX type was also thought to be partially responsible. Another example was event ID672, where incompetence in developing and following procedures led to an explosion and nuclear waste release to the atmosphere and water. These incidents evidenced the importance of clear instructions and use of ATEX type equipment in hydrogen systems.

5.3.1.5 Training and procedures to avoid accidental generation of hydrogen

In Section 4.1, hydrogen generation due to malfunction was linked with several incidents. In event IDs49, 192, 234 and 321, hydrogen was produced during undetected chemical reactions between acids and metals; and in event ID123 hydrogen was produced through unexpected chemical reactions. Wrong identification of chemical components was found to accidentally led to hydrogen generation, resulting in a strong explosion in event ID530. These incidents indicated that human factors could also result in accidentally generated hydrogen. Appropriate training and strict operating procedures and instructions could have helped to reduce/avoid such incidents.

5.3.1.6 Reoperation after repair

The fire in event ID579, which resulted from an escape of liquid hydrogen from a joint between an isolating block valve and a relief valve on one of the separation column preheater, occurred when the relief valve was firstly brought back into operation following repair. Adequate checking to confirm that it was safe to resume operation in the section of the plant could have prevented this incident.

5.3.1.7 Insufficient purging when re-using tanks or pipes previously containing flammable liquid or gas

Lessons from event IDs 531, 631, 750 and 752 suggested that without complete degasification supported by instruction for the appropriate procedure, re-use of tanks or pipes previously contained flammable liquid or gas is prone to incidents. The explosion in event ID 673, for example, was because the furnace was not fully purged/ventilated, the employer did not have a portable gas detector and the safety procedure was not followed.

5.3.1.8 Highlighted incidents with good lessons to be learnt for relevant operators

Event ID 477, which involved an explosion of hydrogen storage tanks of a small fuel-cell power system in the eastern port city of Gangneung (South Korea) in 2019, occurred during a test operation at a venture complex. The three tanks of 40 m³ capacity each were all destroyed in the explosion which sent debris scattered in an area well over 3,000 square meters. The preliminary investigation indicated that the hydrogen and buffer tanks exploded due to static spark in buffer tank while oxygen concentration exceeded 6% and identified several jobs factor related issues which are very important lessons to be learnt:

- The oxygen removing component was omitted during system design. Although the designer included oxygen remover in the initial design, it was removed when constructor notified no oxygen remover was available.
- The buffer tank static spark remover was omitted during construction. It should have been connected to earth but was not because the constructor found there was concrete foundation underneath.
- The operator made mistake by running water electrolysis system lower than the operation power level, which induced increase of oxygen concentration.
- The system had to be operated higher than 98 kWh since the water electrolysis had asbestos type separation membrane. Due to solar panel limitation, the system often operated below 98 kWh.
- The oxygen concentration was detected to be higher than 3% prior to the incident. This would necessitate the installation of an oxygen detector and remover. However, the operator ignored this issue and continued the operation to reach 1000 hours of required experiment validation time.

- The system oxygen concentration was higher than 3%, but the oxygen detector and remover were not installed to cut cost.
- The safety management team did not follow safety regulation to monitor hydrogen quality on daily basis.

Avoidance to make similar mistaken could help to prevent incidents like this.

Incident ID1096 at a petrochemical plant, which involved an explosion on a compressor, highlights the consequences of replacing experienced operators with volunteers on a weekend who had not received adequate training.

5.3.1.9 Lessons learnt related to individual/human factors

Lack of adequate staff training was identified to be the cause of many incidents. Some incidents occurred because the training procedure was insufficiently stringent and updated at regular intervals in line with operational changes. These resulted in a significant number of incidents being caused by human error. The following are some examples to illustrate that avoidance of similar mistakes could have helped to prevent such incidents:

- Some key interventions critical for plant operation were bypassed, ignored or silenced by the responsible personnel (blockage devices, alarms of extreme intervention, etc.), e.g. event ID538.
- Some hydrogen truck drivers were not well trained of the hazards associated with hydrogen (event IDs754, 755 and 756), aware of the need to avoid routes in the vicinity of buildings and people during transportation, event ID719, check the clearance height of bridges when using an FC-bus (ID1003) and park on a weak ground (ID1133).
- Some incidents were caused because the pressure of the filter was not monitored, e.g. event ID661.
- The system was not purged regularly, e.g. event ID 661 or with sufficient nitrogen, e.g. event ID663.
- The design and operation conditions were not adequately verified, e.g. event ID664.
- Emergency procedures were not followed and updated, e.g. event ID665. Another example was event ID666, in which because the start-up procedure was not correctly followed, local runaway reaction was triggered during the start-up.
- Lack of training about procedures to deal with accidentally generated hydrogen was also responsible for some incidents. For example, event ID681 was caused by lack of purging

of the accidentally generated hydrogen. Event ID688 was caused by hydrogen escaping when a vent valve was opened for inspection of a cap and a similar event also occurred 5 years ago, indicating consistent lack of adequate staff training and inspection procedure. Some very good practical lessons can also be gathered from ID685 concerning the consequences of not providing appropriate training for operating staff for isocracker compressor.

- Some incidents, e.g. IDs495 and 686, were caused by lack of efficient communication between shift and day staff, and inadequacy in key routine tasks including the frequency of plant inspections.
- Event ID701 was partially due to insufficient consideration about the pressure of volatile hydrocarbons in the refinery storage tanks with regards to dipping and sampling procedures and when giving clearance for tank entry and repair work.
- Some incidents were caused by workplace safety violation, e.g. ID429.
- Event ID614 was also traced back to human factor, unsuitable action/ operation and operation mistake/ work mistake.

5.3.1.10 Highlighted incidents with good lessons to be learnt for relevant operators

Event ID429, which involved an explosion at a bio-fuels research laboratory, occurred when a visiting research fellow was transferring hydrogen, oxygen and carbon dioxide into a low-pressure gas cylinder to be used as a bacterial growth medium. The explosion was the result of a pressure gauge sparking, setting off the flammable gas mixture involving 15 violations of workplace safety. The incident highlight the absolute importance of following the requirement and instruction for workplace safety in research laboratories.

Event ID494 concerning hydrogen leak inside an auxiliary building in a nuclear power plant also resulted in some important lessons to be learnt. These include the need to maintain appropriate in-plant communications during incidents, appropriate valve application for use with hydrogen, excess flow check valve set point, heating ventilation and air conditioning (HVAC) maintenance and flow testing, hydrogen line routing.

5.3.2 Lessons learnt related to organization and management factors

Management and organization factors are also a significant cause of incidents. Among all the incidents whose cause originates from these factors, the following lessons need to be learnt:

- Some incidents were traced back to the lack of up-to-date inspection plan, infrequent inspection frequency and insufficient scope of the inspected components.
- The maintenance procedures were modified following some incidents, indicating insufficient check of safety equipment, leakage tests and lack of inspection for hydrogen embrittlement.
- Some incidents occurred because the security processes prescribed for the modification and /or improvement of the plants, especially when external companies were used, were not sufficiently stringent. Some incidents indicated the lack of safety supervision during certain repairing works and the need for extreme precautions when soldering, using grinding machine or impact wrench (ID631). Regarding welding, event ID496 involving a hydrogen gas combustion inside a pressurizer was caused by welding activities associated with the pressurizer loop seal modification had ignited the hydrogen gas that had come out of solution and accumulated inside the pressurizer and associated piping. The incident resulted in the licensee imposing additional controls for welding on the primary system, requiring the samples be taken and analysed before initiating an arc to determine if explosive gasses were present.
- Some incidents could have been prevented by procedures for fast isolation of the release sources.
- Some incidents were traced back to lack of clear guidance about the lifetime of critical components in addition to their regular inspection and replacement.
- Event ID546 was due to lack of explosivity control before maintenance on a running plant.
- Event ID563 was due to lack of clear distinction between emergency and operating alarms in hydrogen system units.
- Event ID1096 was partly due to the failure to investigate a precursor incident, which meant that the risk assessments were not reviewed.
- Although this was an incident involving a natural gas pipeline, event ID1100 illustrates a rupture caused by hydrogen cracking at a weak point, with very serious consequences for human life. Investigations showed that the company had not adequately considered the conditions within the pipeline and the effect of combined threats in its risk analyses.

5.3.2.1 Highlighted incidents with good lessons to be learnt for relevant operators

The explosion in event ID525 due to accidental release of hydrogen at the Institute of Energy Conversion, University of Delaware, was related to the absence of a formal policy for the systematic oversight of gas handling and safety systems. The direct cause resulted from an operator error in opening a valve in the wrong sequence resulting in the discharge of hydrogen at pressure >1100 psi through an open valve into a vacuum system not rated for this amount of pressure.

5.4 Lessons learnt for the first responders

The lack of insight and knowledge due to insufficient training of the technical personnel, mentioned in Section 5.3.2 is also applicable to the personnel of the emergency services. As hydrogen energy applications are still relatively new, first responders are generally less equipped with the knowledge about the various accident scenarios they may encounter and do not know enough about how to respond. This statistical analysis has therefore directly contributed to the updating of the European Emergency Response Guide²².

One example that shows that the consequences of the incidents can be worsened due to inadequate preparation of the emergency personnel, is event ID357, in which a hydrogen leak occurred during a transfer of liquid hydrogen from a commercial tanker to a stationary receiving vessel, produced a hydrogen spray which enveloped the rear of the truck where the hand-operated shutoff valve was located. The emergency personnel who went to close the valve were wearing protective clothing except proper shoes, suffering frostbite of their feet when entering the area.

Quick action to limit inventories could help preventing the escalation of an incident. In responding to event ID487, which involved 60 feet jet flames from compressed hydrogen gas inside a tanker truck, firefighters climbed on the tanker truck during the incident to shut off the other nine tubes so their contents would not burn off as well. Prompt rapid action to limit inventories is an important lesson to be learnt. Of course, this is only possible if, together with the emergency services, prior intervention plans are provided with crucial and relevant technical information. The

²² <https://hyresponder.eu/e-platform/european-emergency-response-guide/>

installation and the specific emergency operation in function of the different incident scenarios must be known to the intervening emergency service. Dedicated consultation and common exercises and trainings are very important.

Poor drainage can inhibit the effectiveness of emergency response. Event ID547 indicated that firewater drainage is a longstanding problem at many disaster sites. The installation of a draining system in the construction plans of the plant (fire prevention advice) will help to improve the effectiveness of emergency response in case of an incident.

Lack of sufficient evidence gathering has hindered some investigations. The explosion in ID575 was one of the largest industrial hydrogen explosions reported till the date. The accident occurred due to a combination of operational error, technical failures and weakness in the design. The explosion caused large number of fragments representing a severe hazard with window glasses being broken up to 700 m from the centre of the explosion. Domino incidents such as fires were behind the severity of this incident, and common after many gas explosions. The investigators drew some important lessons including delayed documentation of the damage; lack of involvement from explosion expert and structure engineers; lack of photographic evidence covering both area view and specific damages to aid the investigations; and insufficient collection of fragments, their original and landing positions and damage indicators to aid accident investigation.

Extinguishing the fire while hydrogen was still escaping could result in more serious hydrogen explosions. This is an important lesson to be learnt as hydrogen is highly explosive.

Event ID539 clearly indicated the importance of efficient safety crew to manage some fire incidents.

Event ID1003, involving an FC-bus, is of significance to the first responders because a misplaced pressure gauge provided incorrect information about the hydrogen content in the tanks, and switching off the main power switch did not eliminate all electrical risks.

5.5 Lesson Learned with respect to LH2 events

This section provides lesson learnt extracted from the JRC analysis on some of the new events related to LH2 applications.

Event ID: 320

Date Range: 1950–1974

Location: United States, North America

System/Component: Liquid Hydrogen (LH2) Storage Tank

Damage/Losses: Unknown

Description: Following pneumatic/thermal testing of an LH2 tank, the vessel was flushed with helium gas for over four hours to inert the environment. The tank's main flange was subsequently removed to insert a smaller experimental sub-tank. Due to residual cryogenic temperatures within the system, atmospheric air entering the vessel underwent rapid cryo-pumping and liquefied. This concentrated liquid air (oxidizer) came into direct contact with residual hydrogen gas (fuel) that had bypassed the helium purge. A hot-wire platinum sensor, operating above the autoignition temperature of hydrogen, served as the ignition source, triggering a severe explosion.

Root Causes:

- Inadequate and unverified purging procedures.
- Failure to empirically measure and verify internal hydrogen concentration prior to opening containment.

Lessons Learned and Safety Principle Violations:

SP3 Violation (Ignition Source Control): Open, high-temperature electrical components (such as hot-wire sensors) should not remain energized inside a vessel when containment is breached, as they pose an immediate ignition risk if an atmosphere is introduced. It is always good idea to remove and minimize known ignition sources (and known ignition mechanism) when working with H2 to make sure that ignition never happens in case of unintentional formation of H2-air mixtures.

SP9 and SP10 Violations (Lack of H2 safety knowledge and lesson learnt from previous incidents): The purging success must never be assumed based solely on time of the operation.

Operators must independently sample and verify gas concentrations before opening any hydrogen vessel to the atmosphere.

Event ID: 327

Date Range: 1950–1974

Location: United States, North America

System/Component: Liquid Hydrogen (LH₂) Storage Tank

Damage/Losses: Unknown

Description: During the decommissioning and dismantling of a hydrogen cryostat, technicians encountered a frozen or seized mechanical coupling. To free the coupling, a commercial hot air dryer was introduced as a heat source. Residual hydrogen gas remaining inside the unpurged cryostat leaked or breached containment near the work area, mixing with ambient air. The internal heating elements or electrical contacts of the hot air dryer exceeded the minimum ignition energy (MIE) and autoignition temperature of the hydrogen-air mixture, resulting in an immediate flash fire.

Root Causes:

- Failure to verify complete isolation and purging of flammable gases prior to mechanical disassembly.
- Introduction of an unrated, non-intrinsically safe ignition source (hot air dryer) into a hazardous zone.

Lessons Learned and Safety Principles Violations:

SP3 Violation (Ignition Source Control): Hydrogen has an incredibly low Minimum Ignition Energy (MIE) and a wide flammability range (4 to 75% in air). Using a standard commercial heat gun—which features exposed internal electrical contacts and glowing heating elements—guaranteed ignition the moment the residual hydrogen leaked. In hazardous zones, only tools rated as intrinsically safe or explosion-proof are permitted, and strict hot-work permit procedures must be followed.

SP9 and SP10 Violations (Lack of H₂ safety knowledge and lesson learnt from previous incidents): A fundamental tenet of hydrogen safety is to *never* break containment on a system until it has been completely isolated, depressurized, and purged with an inert gas (like nitrogen or

helium), followed by gas testing to verify a zero-energy state. Proceeding with mechanical disassembly and applying heat to an unverified system points to a critical gap in training and a failure to apply well-established industry lessons regarding hydrogen fire hazards.

Event ID: 357

Date Range: 1950–1974

Location: United States, North America

System/Component: Liquid Hydrogen (LH2) transfer tanker

Damage/Losses: 4 injuries

Description: During a transfer of liquid hydrogen from a commercial tanker to a stationary receiving vessel, a leak developed in the bayonet fitting at trailer-vessel connection. The leak produced a hydrogen spray which enveloped the rear of the truck where the hand-operated shutoff valve was located. Emergency trained personnel, wearing protective clothing, except for proper shoes, entered area and shut off flow control valve. The personnel suffered frost-bite of their feet when shoes became frozen to water-wetted rear deck of truck.

Root Causes:

- Inadequate design of a flange connection sealing material for LH2 causing the hydrogen spillage and spray.
- Inadequate system design for accessibility to hand-operated shutoff valve
- Use of inadequate personnel protective equipment for LH2 emergency intervention actions.

Lessons Learned and Safety Principles Violations:

SP0 Violation (Proper design and material selection for hydrogen applications): Any system/component leading with LH2 shall be properly designed to withstand extreme temperature conditions (cryogenic temperatures) guaranteeing no degradation in properties. Additionally, emergency devices (like shutoff valves) shall be made accessible by design.

SP9 (Lack of H2 safety knowledge/training): Understanding specific risks of liquid hydrogen spills (cryogenic conditions) is key to define emergency protocols and required emergency protection equipment.

Event ID: 1076

Date Range: 1985

Location: United States, North America

System/Component: Liquid Hydrogen (LH2) stationary storage tank

Description: Prior to repairing a vent on a stationary LH2 storage tank (34 m³ insulated with perlite), the tank was drained. Initially, it was purged with nitrogen, but due to the slow evaporation rate of LH2, it was decided to use the vacuum valve to speed up the process. First with the valve slightly open and then fully open. The pressure then rose very rapidly in the tank, leading to its explosion.

Root Causes:

- The root cause can be clearly identified as human error following the opening of the vacuum valve.
- A procedure was apparently in place involving nitrogen purging, but external factors (job factors) made it necessary to speed up the venting process by applying more heat to the cryogen.
- A clear and relevant procedure (management factor) based on risk assessment analyses must support any decision.

Lessons Learned and Safety Principles Violations:

SP8 Violation (Provide efficient passive safety barriers): On a liquid hydrogen tank, the safety systems (safety valve and burst discs) must be designed to deal with the scenario of air ingress in the insulation vacuum, regardless of the conditions (internal pressure, filling level) and the plausible source of heat transferred to the cryogenic fluid.

SP9 (Lack of H2 safety knowledge/training): Understanding specific risks of liquid hydrogen boil-off and venting is key to define relevant safety systems (safety valves and burst discs) and adequate procedure based on risk assessment analyses.

Event ID: 609

Date Range: 1974

Location: United States, North America

System/Component: Liquid Hydrogen (LH2) Storage tank

Damage/Losses: 1 injury

Description: A rupture disc opened on a 76 m³ (20,000-gallon) liquid hydrogen tank, causing the vent stack to release cold gaseous hydrogen. The gas ignited causing a fire on the vent stack's outlet. Emergency responders intervened by removing the remaining hydrogen but left a small volume which could not be removed manually. During this operation, the vacuum system lost its heat isolation capacity due to a (presumed to be mechanical) failure. This triggered a rapid evaporation of the residual liquid hydrogen with consequent increase of the tank internal pressure. In answering to this, the emergency responders sprayed the tank with water and directed a stream onto the fire exiting the vent stack. The water jet was pointed directly into the open vent stack, thus interacting with hydrogen vapours from the residual hydrogen (between -253 °C and -241 °C). This caused the water to freeze in the vent stack. This ice blocked the stack, which was the only exit for the cold hydrogen gas. Eventually, all residual hydrogen in the tank warmed up, causing the tank to over-pressurize and rupture with an explosion known as a BLEVE (Boiling Liquid Expanding Vapour Explosion).

Root Causes:

- Inadequate management of emergency response to incident and lack of adequate protocols and emergency procedures

Lessons Learned and Safety Principles Violations:

The initiating event in this incident was the opening of a burst disk and release of H₂ that should not have been progressing to worse consequences. However, the incident escalated to an explosion (BLEVE) due to wrong decisions/actions of the emergency responders, to which probably contributed the lack of emergency procedures of the plant, up to a lack of proper risk assessment.

SP9 (Lack of H₂ safety knowledge/training): Understanding specific risks of liquid hydrogen (cryogenic conditions) is key to define emergency protocols and required emergency protection equipment. This case showed also that water as emergency means to stop fire has to be used with caution in case of LH₂, due to the possibility of water freezing and consequent obstruction of the available gas release devices. On the other side, in cases involving fire of compressed

hydrogen, water jet was effective to cool down the tanks and avoid that they reach overpressure. Therefore, emergency teams have to be informed in detail on the nature of the hydrogen storage affected by an incident.

Event ID: 1220

Date Range: 09/01/2025

Location: France, Europe

System/Component: Liquid Hydrogen transfer hose

Damage/Losses: Unignited hydrogen release and no damage

Description: A liquid hydrogen leak occurred at a high-Tier Seveso aerospace facility specializing in cryogenic propellants. During the purging of hoses after unloading a 53 m³ liquid hydrogen road tanker, personnel detectors alarming above 10% LEL, coupled with observed liquid flow and white vapor plumes from the tank's rear, signalled the leak.

The cause was a partially closed bottom valve on the tanker, leaking liquid hydrogen which subsequently liquefied ambient air on the uninsulated hose surface. Increased hydrogen release from the vent stack, blown towards operators by the wind, facilitated early detection. White plumes were due to cold, humid conditions favouring air liquefaction and moisture condensation. The emergency stop was activated, the facility shut down, and the area sprinkled. Operators restored safety by: (1) opening tanker valves to flare hydrogen, reducing pressure/leak flow; and (2) injecting helium downstream of the bottom valve to dilute hydrogen and warm the valve, allowing it to be fully closed.

The emergency plan was deactivated after approximately 7 hours. No injuries were reported.

Root Causes: A material failure, but a mistake in the execution of the transfer procedure cannot be excluded

Lessons Learned and Safety Principle Violations:

SP0 and SP9 Violations (Proper design and material selection for hydrogen application and Lack of H₂ safety knowledge): The tank's bottom valve partially closed, likely due to a mechanical blockage from an ice plug of unknown composition. This blockage was probably caused by unexpected low temperatures during unloading and possibly worsened by a loss of vacuum in the valve's double-walled enclosure or adjacent piping. All safety systems worked as

intended. The appropriate materials shall be selected. Before and after the transfer operation the hose, all connections and valves shall be visually examined. The operation procedure shall be written and followed by the trained personal.

Event ID: 1223

Date Range: 20/05/1990

Location: United States

System/Component: A flange at the temperature of the liquid hydrogen

Damage/Losses: Hydrogen leak without ignition delaying launch of a space rocket

Description: LH2 leak when fuelling a rocket tank

In 1990 the Space Shuttle fleet was grounded for several months by an elusive hydrogen leak occurring during the procedure of fuelling of the liquid hydrogen tank of a space shuttle.

The Columbia launch was scheduled on the 30th of May 30, when personnel discovered a hydrogen leak during tanking. The external fuel tank was loaded through an orbiter. Liquid hydrogen flowed through a 17-inch umbilical between the orbiter and the tank. During fuelling, the aft fuselage was purged with gaseous nitrogen to reduce the risk of fire. Moreover, a leak-detection system was installed on the mobile launch platform, sampling the atmosphere in and around the vehicle, and bringing it to the ground to a mass spectrometer for gas composition analyses. When starting the tanking with liquid hydrogen, hydrogen concentration approached four percent-the limit above which it would become flammable. Various attempts were executed to identify the location and the cause of the leak.

Eventually, a series of leak detectors installed outside the orbiter, where the umbilical was connected to the external tank showed the greatest concentration of hydrogen. The leak had to be at the seal which has already been replaced and rigorously inspected.

After the adoption of measures to avoid the repetition of this occurrence, the 6th of October 1990, the discovery was able to take off, the first launch since April.

Root Causes: The INITATING CAUSE was the reduced sealing capacity of a flange at the temperature of the liquid hydrogen.

The flanges had passed the qualification test at the manufacturer site, because the manufacturer tested it with liquid nitrogen, instead of liquid hydrogen. The latter was not permitted at the site.

ROOT CAUSES can be identified in an inadequate qualification procedure by the manufacturer, and in a lack of management safety and quality control of contractors by the plant owner.

Lessons Learned and Safety Principle Violations:

SP0 and SP9 Violations (Proper design and material selection for hydrogen application and Lack of H2 safety knowledge): This event confirms how difficult is to identify the exact location of hydrogen leak in complex technical systems. Due to its volatility, the leaking hydrogen quickly diffuses into the space around the leak, so that several fixed detectors placed in different positions can detect hydrogen simultaneously.

The manufacturer only tested the seals with liquid nitrogen, not liquid hydrogen. It was not possible for them to use hydrogen due to vicinity of densely populated areas. Liquid nitrogen was a safe alternative, with the consequence that the flange was tested at -196°C instead of -253°C. On top of that, nitrogen molecules are much bigger than hydrogen ones, and diffuse less easily.

Event ID: 1225

Date Range: 03/09/2022

Location: United States

System/Component: Flange at the temperature of the liquid hydrogen

Damage/Losses: Hydrogen leak without ignition delaying launch of a space rocket

Description: Hydrogen leak delaying launch of a space rocket

The event occurred during the fuelling process of the primary fuel tank of the core stage of a moon rocket. The initial slow-filling phase was terminated, and personnel had just started the fast-filling phase when a leak was detected on a quick-disconnect fitting of the liquid hydrogen line into the tank. Hydrogen was leaking into the purge can, which is a housing covering the quick disconnect fitting, part of the tail service mast umbilicals. The leak was exceeding the concentration limit of 4%, set by flammability risks, by a factor of two or three.

Engineers made several attempts to reseal the fitting on-site and on-launch, by allowing it to warm up and replacing the seal, or by closing the fuelling valve and drain it, then increasing

pressure on the ground transfer line using helium to force the fitting back into place. Eventually, the launch on 3rd of September had to be postponed.

In the following days, engineers troubleshooted the leak. During the cryogenic tests, the 21st September, already during the slow-filling phase a leak at the same location was detected. The connection was again warmed up and refixed, and the filling operation continued at lower pressure than before. This time the hydrogen concentration in the housing remained under the allowed limit, and the refuelling could continue up to full fill and the pressurisation tests.

During the next launch attempt, the 15th of November, the fast-fuelling phase was successfully completed, but a valve at the base of the mobile launcher, used to replenish the core stage with hydrogen, showed a leak above safety limits. The hydrogen flow was stopped, and a team of engineers had to go to access the pad and tighten several bolts to troubleshoot a valve. The rocket lifted off one day later.

Root Causes: The INITATING CAUSE was a hydrogen leak from a liquid hydrogen connection, above the allowed maximal concentration in air.

One possible reason of the loss of confinement capacity of the connection could have been an error of over-pressurisation of the liquid hydrogen line of the quick-disconnect interface, which may have damaged a seal. During the early phase of hydrogen transfer operations called chill-down, aiming at cooling down the lines and propulsion system prior to flowing liquid hydrogen, an inadvertent command was sent that temporarily raised the pressure in the system.

A second explanation of the leak could have been a small indentation on the eight-inch-diameter liquid hydrogen seal, found during the post-mortem examination of the seal.

These sources do not identify with certainty a ROOT CAUSE. From the suggested leak explanations, it derive that one root cause factor could have been the cryogenic procedure.

Lessons Learned and Safety Principle Violations: SP9 Violations (Lack of H2 safety knowledge): This event, prolonged throughput several weeks, is similar to an earlier case of elusive leaks related to the launch of a space shuttle, a period called by NASA the ‘the summer of hydrogen’ (see HIAD_1223).

It shows how difficult is to identify the exact location of hydrogen leak in complex technical systems. Due to its volatility, the leaking hydrogen quickly diffuses into the space around the leak, so that several fixed detectors placed in different positions can detect hydrogen simultaneously. Despite the progress in fundamental knowledge of liquid hydrogen behaviour and in engineering system dealing with a liquid at the most

extreme temperatures, loss of confinement remains a concern. In this recent case, however, engineers required much less time than back 20 years ago to troubleshooting the leak.

Event ID: 1224

Date Range: 01/11/2011

Location: United States, North America

System/Component: The liquid hydrogen tank vertical cylindrical structure with a volume of 340.7 m³ (a capacity of 25 metric tons of hydrogen). It was built in 1962 and its outer tank was made of carbon still.

Damage/Losses: No hydrogen release and crack of the outer shell of the liquid storage

Description: A large LH₂ storage tank at an aerospace testing facility suffered a major vacuum leak in its insulation annulus, eventually leading to cracks in the carbon steel outer shell. Despite leaks in two rupture disc assemblies and a pressure rise in the annular space, the tank remained operational for an incumbent rocket engine test. A liquid top-off induced cryo-pumping, dropping the annular pressure from 9332.6 Pa to 3.1 Pa. After the test, the tank was drained for repair. Two days post-drain, heavy frost appeared on the outer vessel bottom, with temperatures below 90 K, which is below the carbon steel's ductility range. Attempted vacuum pumping was difficult due to port size/perlite intrusion. Eighteen days after draining, the outer vessel cracked.

Root Causes: Manufacturing error and/or exceeding of number of thermal cycles and the choice of low strength carbon steel for the material of the outer shell.

Lessons Learned and Safety Principle Violations:

SP0 and SP9 Violations (Proper design and material selection for hydrogen application and Lack of H₂ safety knowledge): This is a near-miss event, where an LH₂ tank operation was stopped before the external shell cracked. Unlike typical leaks, the extremely low temperatures freeze most air components near the inner tank wall. Only trace helium and neon cause a minor pressure increase, often going unnoticed for months or years. The first sign is usually an increase in the boil-off rate, as frozen air (perlite contamination) increases thermal conductivity, causing a significant heat leak. Contributing factors include the use of corrosion-prone carbon steel for outer walls and the potential failure of soft seals over time. Long-term

monitoring of annular pressure can detect a leak and estimate the rate by analyzing the known fractional content of helium and neon in the air, allowing an estimate of the total air ingress.

Event ID: 782

Date Range: 04/05/2008

Location: United States, North America

System/Component: PRD (burst disk) of the LH2 storage

Damage/Losses: Unignited Hydrogen Release, the only property loss was due to the loss of hydrogen.

Description: A liquid hydrogen (LH2) storage vessel (9,000-gallon/34,069-liter) at an urban manufacturing plant vented hydrogen when its internal pressure exceeded the maximum limit, causing a burst disk to activate. The hydrogen jet rose 4-6 meters but did not ignite.

The industrial gas company's technician found the tank at zero pressure with the burst disk blown. They switched the diverter valve and replaced the activated disk. The safety venting equipment worked as designed; the release was outdoors, preventing gas accumulation. Operations resumed safely. Seven months later, the replacement burst disk ruptured for the same reason. Again, the pressure relief system functioned as designed, and no emergency response was needed. No injuries or damage occurred in either incident.

Root Causes: The temperature increase (normal functioning) and heating up of the liquid hydrogen inside due to period of unused of the liquid inside the tank. A factor contributing to a premature activation was the existence of a backpressure against the disk.

Lessons Learned and Safety Principle Violations:

SP0 and SP9 Violations (Proper design and material selection for hydrogen application and Lack of H2 safety knowledge): The hydrogen venting worked correctly, but several recommendations arose from the incident:

1. Local emergency responders lacked adequate training on hydrogen behaviour and safety to effectively intervene. Specific training on H2 specific aspects is necessary.
2. Unused liquid hydrogen installations, especially those containing significant hydrogen, require regular inspection by facility personnel to check operation and identify damage/leaks. In the US, inspections should follow NFPA 55. The deviations to this require contacting the servicing company.

3. In the US, the Compressed Gas Association (CGA) publishes guidelines for liquid hydrogen installations (G-5.4, G-5.5, H-3, H-5).

5.6 Highlighted incidents with good lessons to be learnt related to cascading failure

Below, three incidents, which involved several relatively minor causes combined to result in cascading series effects, are highlighted:

Event ID 653 started with an explosion, followed by a hydrogen fire in the hydrogen compression building. The fire ignited roofing materials which had fallen down as the result of the explosion. The operator, who was outside the plant when the explosion occurred, pulled the emergency switch which shut down all the compressors. The fire alarm was raised by the Gatekeeper who had heard the explosion and seen flames and smoke in the vicinity of the hydrogen plant. The onsite fire team was quickly on the scene but were advised not to extinguish the fire while hydrogen was still escaping to prevent the likelihood of further explosion. The supply of hydrogen to the compression plant was cut off and the plant was electrically isolated before the arrival of the County Brigade. The compressor involved had recently been overhauled and handed back to production on the day before the explosion. It ran satisfactorily for an hour before being shut down to fix clamps on the high-pressure cooling coils which were vibrating. It was restarted in the following morning and again ran without signs of trouble until the explosion occurred after nearly an hour in operation. After the explosion, a pressure gauge, with associated piping and isolating valve was found on the floor near a wall. It was concluded that the initial cause of the explosion was the failure of the coupling. Although all the similar couplings were checked and found to be satisfactory, it was noted that if this type of joint fails, the consequences are likely to be more serious than failures of other types of high-pressure joints.

The explosion in event ID698 in a polyethylene manufacturing plant was caused by a flammable cloud escaping from a reactor during maintenance, resulting in 23 fatalities and 314 injured workers. It led to some serious lessons to be learnt to prevent such cascading effects:

- Not conducting hazard analysis or using an equivalent method to identify and assess the hazards of the installation in the design stage could have serious consequence;
- Insufficient separation distances between process equipment plant would result in insufficient time for personnel to leave the plant safely in case of emergency;

- Insufficient separation distance between the control room and the reactors would result in insufficient time to allow emergency shut down procedures to be carried out;
- Inadequate locations of the ventilation intakes of buildings close to or downwind of the hydrocarbon processing plants could result in accidentally released gases being drawn into the ventilation network;
- Inadequate design could result in unnecessary exposure of personnel to potential hazard;
- No flammable gas detection system in plants with a large inventory of flammable materials could have serious consequences;
- An effective permit system was not enforced for the control of the maintenance activities;
- Lack of double block system or blind flange; and
- Relying on the process water system for fire fight making it vulnerable to an explosion.

Event ID 598 was an explosion resulting from a series of human errors and component weak points during a reduction process for the manufacture of para-phenetidine (PPD). Firstly, workers did not firmly close a valve on discharge pipes of para-nitrophenetole (PNP) and forgot to close a valve fitted with an air-operated flow meter. This led to hydrogen leak into the PNP discharge pipes. With defects on the welded part of the pipes and corrosion by chlorine in PNP, the pipes fractured to allow hydrogen to escape into the insulation cover of the PNP tank, where it accumulated to form explosive gas, which was ignited by electrostatic sparks generated when hydrogen was ejected.

Event ID1051 reports a hydrogen/nitrogen gas release occurring in the building containing the pump for the recirculation of process gas of a plant producing fertilisers. An outlet valve of a compressor had been identified as defective several years before but had been kept in place. During repair works aiming at replacing it, it failed open releasing a large quantity of process gas and enabling the formation of an explosive gas mixture. Delayed ignition took place nine minutes after the release, so that the mixture could form not only in the compressors building but also diffuse into the neighbouring rooms, before it ignited. Explosions had huge human and materials consequences. The incident was primarily caused by an underestimation of the critical role of safety for specific components. The malfunctioning compressor valve was allowed to operate for years, with the operational team using unofficial, improvised solutions to compensate for its failure. These practices were not documented in the procedures, leading to potential oversights, especially during high-stress situations. An investigation revealed a significant failure in the company's safety management, characterized by a poor safety culture and inadequate technical

knowledge. Key issues included a lack of safety awareness among managers and some employees, the persistence of known equipment failures without effective resolution, and the non-enforcement of rules and regulations. This degradation of safety management highlights the importance of maintaining robust safety protocols and a strong safety culture to prevent such incidents.

In recent years, liquid hydrogen has become an important energy carrier for heavy-duty transport. It is therefore worth highlighting a few significant safety-related events and the associated lessons learnt.

Event ID1076 clearly illustrates that the absence of clear procedures and poor judgement from the operator can have serious consequences. In this case, the venting of a liquid hydrogen tank was accelerated by the opening of the isolation vacuum valve, causing the cryogen to boil and the tank to rupture catastrophically.

A cryogenic vessel will always produce some boil-off gas even with the insulation jacket. This requires frequent inspection (ID1050) and, potentially, manual venting. Moreover, a pressure relief device able to release the excess this boil-off gas and to maintain the internal pressure below the design value should be always present. However, during the opening and closing cycles of these valves, ice may form and the seal may leak (ID379 or ID375).

6 RECOMMENDATIONS

This section includes recommendations in our previously published report² in 2021 as a new section based on the analysis from the newly added events involving liquid hydrogen. The later aims at providing some general recommendations distilled from the newly added LH2 events in HIAD 2.4. Although all the incidents included in the analysis were related to incidents occurring in operating installations, the design aspects have been also considered in the recommendations as it can be an effective mean to prevent incidents through inherently safer design.

Note recommendations are extracted for few cases which are reported on lesson learnt. More comprehensive lesson learnt and recommendations will be shared when this report is updated and issued again.

In formulating the recommendations, links are made to the relevant Safety Principles wherever possible. The recommendations are formulated according to system design, ignition source minimization, human interaction and liquid hydrogen systems.

6.1 Recommendations related to system design (SP0)

It is important to highlight the specific importance of design the equipment inherently safe from risk of LH2.

- The materials should be compatible for usage of LH2 (for example outer jacket should be designed with Stainless steel not carbon steel – mentioned **event ID 1224** or containment and welding material which results in no H2 embrittlement – see **event ID 357**).
- Tanks and the pipes should be design with redundant (independent) safety relief valves where possible, in this way if one of the pressure relief is not working other redundant pressure relief can be used (see **event ID 609**).
- To label the pressure relief vent opening with **No WATER** exposure as indication to the fire fighter that they are not supposed to cool the vent pipes (see **event ID 609**).
- To design safe, decommission process (for example, in case of decommissioning of LH2 tank, the tank should be purged with many cycles of inert gases e.g., N2 or helium to make sure there is no residual H2 is present - see **event ID 320 and 327**). Before breaking containment, opening a flange, or dismantling any component, operators must use calibrated, intrinsically safe hydrogen detectors to sample the internal atmosphere at multiple physical elevations to rule out stratified gas pockets.

- To design regular monitoring the temperature and pressure inside LH2 tank in case of temperature or pressure excursion, the system should be safely isolated.
- The vent outlet system should be designed in such way there is no risk in case of normal and emergency venting of H₂ (for example the vent opening should be cited at a height such that ignition of vented H₂ does not have any impact on people and assets).
- Manual hand-operated shutoff valves must not be located directly beneath or adjacent to high-risk leak points like flange connections or trailer bayonets (**Event ID 357**). Furthermore, emergency isolation valves should either be automated (fail-safe pneumatic/electric) or physically routed so operators can access them from a protected and upwind vantage point.
- Mechanical connections and bayonet fittings must appropriate material and specialized cryogenic soft seals designed to maintain elasticity at -253 °C to prevent continuous leaks and sprays during liquid transfer (**Event ID 357**).
- Systems must be allowed to warm up above cryogenic temperatures, or maintained under a positive pressure of pure helium or nitrogen gas, before opening containment to ensure ambient air cannot enter (**Event ID 320 and 1224**). As air entering the LH₂ tank atmosphere triggers immediate cryo-pumping.
- For double-walled vacuum-insulated vessels, real-time, continuous monitoring of the annular insulation space is vital (**Event ID 1224**). A subtle pressure rise combined with an increased boil-off rate points to ambient air or hydrogen leaking into the perlite insulation. Analyzing the fractional content of trace gases (like Helium and Neon) within the vacuum space can help engineers locate the source of an internal containment breach before an external failure occurs.

6.2 Recommendations related to ignition source minimization, prevention and PPE (SP3)

- To make sure that ignition sources are minimized and if possible, known ignition sources are completely ruled out (see event ID 320 and 327) even in the absence of flammable mixture.
- Any introduction of a heat source or spark-generating activity must trigger a comprehensive Hot Work Permit system. This permit must enforce a minimum safe clearance radius and require a designated, trained fire watch with a suitable fire extinguisher, etc.

- Emergency response kits and transfer protocols must mandate specialized cryogenic Personal Protective Equipment (PPE). This includes insulated, water-resistant safety boots and gauntlets to prevent severe frostbite if a responder must walk onto decks or surfaces wetted by liquid leaks or condensed air (**Event ID 357**).

6.3 Recommendations related to human interaction/interface (SP9 and SP10)

The education and regular training are essential for safety personal who is involved in design, operation, maintenance (including higher level management), fire-fighting and emergency response. Due to the lack of this education and regular training there is a possibility that hydrogen system has design fault (including material selection) and incorrect installation. Furthermore, it can also contribute to job factor, individual factors, organization and management factors.

In addition, the following specific recommendations have also been formulated:

- Train staff for safe operational management about the following specific aspects:
 - the connection and purging procedure of LH2 tanks, vent lines and transfer hoses.
 - importance of pre-start up safety checks,
- Before connecting and immediately after disconnecting a transfer hose, perform a structured visual sweep of all bayonets, couplings, fittings and adjacent valves. Check for physical deformation, signs of debris, or early moisture condensation that could cause a valve to freeze open or closed during liquid flow.
- Train all maintenance personnel on the physical properties of hydrogen—specifically how liquid or cold gaseous hydrogen can stay trapped in low-lying pockets, pockets blocked by ice/frozen air, or within complex internal geometries of a cryostat even after a primary vent line is opened.

When doing your rounds on vacuum-insulated tanks, instead of just relying on pressure changes based on inner tank pressure sensors., keep an eye out for a sudden, unexplained **increase in the boil-off rate** or unusual frost patches at the bottom of the outer vessel shell. This is a primary indicator that ambient air has leaked into the insulation space and frozen solid, destroying the vacuum thermal barrier.

6.4 Recommendations related to liquid hydrogen systems (SP0, SP3, SP9 and SP10)

- Purging of LH2 tank could leave the residual cryogenic temperatures within the system. This might lead to the atmospheric air entering the vessel undergoing rapid cryo-pumping, resulting in liquefied concentrated liquid air (oxidizer) which might come into direct contact with residual hydrogen gas (fuel). The purging success must never be assumed based solely on time of the operation. Operators must independently sample and verify gas concentrations before opening any hydrogen vessel.
- Do not break containment on a hydrogen system until it has been completely isolated, depressurized, and purged with an inert gas (like nitrogen or helium), followed by gas testing to verify a zero-energy state.
- Any system/component in LH2 systems should be adequately designed to withstand extreme cryogenic temperatures to guarantee no degradation in material properties. Additionally, emergency devices, such as shutoff valves, should be made accessible by design.
- Emergency protocols and protective equipment for LH2 systems should be designed with understanding of the specific risks of LH2 spills at cryogenic conditions).
- On a LH2 tank, the safety systems such as safety valve and burst discs must be designed to be resistant to air ingress in the insulation vacuum, regardless of the internal pressure and filling level as well as potential heat transfer to the cryogenic fluid.
- Understanding specific risks of LH2 boil-off and venting is key to define relevant safety systems (safety valves and burst disks) and adequate procedure based on risk assessment analyses.
- Water to extinguish fire should be used with caution in case of cryogenic LH2, which might freeze the water, resulting in the obstruction of the gas release devices.
- Be aware that if an LH2 tank operation was stopped, the cryogenic temperature would freeze most air components near the inner tank wall. This could often go unnoticed for months or years. It is recommended to look for signs like an increase in the boil-off rate, as frozen air (perlite contamination) increases thermal conductivity, causing a significant heat leak.

- It is recommended to use corrosion-prone carbon steel for outer walls and be cautious about potential failure of soft seals over time. Long-term monitoring of the annular pressure can detect a leak and estimate the rate.

7 CONCLUDING REMARKS

Following the publication of the 2nd report about “Statistics, lessons learnt and recommendations from the analysis of the Hydrogen Incidents and Accidents Database (HIAD 2.0)”, the EHSP Task Force 3 has worked with JRC on HIAD analysis. The present report is the 3rd of the series, which has been updated with the assessment of events added by JRC in the 2022-2025 period under consideration of the upgraded structure of HIAD. To avoid confusion about version numbers, it has been decided to refer to the database as HIAD (without a version number) when describing general issues. The analysis covers statistics, lessons learnt and recommendations on 898 events out of the 1220 events which were in the public available version of HIAD 2.4 in May 2026. Due to the limited time available, it was decided to leave the remaining events to be analysed next year together with any new events that are continuously being added to HIAD. The statistics analysis has included the 598 events that were in HIAD 2021 and included in our previous Report³ plus 305 newly added events in HIAD 2.4. Considering that there are a considerable number of newly added events involving Liquid Hydrogen (LH2), the Lessons Learnt and Recommendations have been updated with a specific sub-section about LH2.

In this 3rd version, Chapter 2 has been updated to provide more complete sources of information used by HIAD and the descriptions about the analysis procedures which were previously scattered in other Chapters have now all been consolidated in this Chapter. This report includes an overview of the events in HIAD2.4 and the updated statistics as summarized above. The lessons learnt have been updated with additional highlighted events as well as a special section related to LH2 systems, for which a new section has also been added to the recommendations.

For completeness, a summary of the **lessons learnt** is as follows:

- Lessons learnt have been gathered in several categories in relation to system design, system manufacturing, installation and modification, operators incorporating jobs factors, organisation and management factors as well as first responders.
- A very important lesson learnt is that cascading effects of minor events could result in extremely serious consequences. Many incidents were caused by multiple factors.
- In relation to jobs factors, some frequently occurred issues were identified as lack of regular maintenance or inspection, lack of appropriate attention for safety devices during maintenance, not following appropriate procedures for pre-start equipment checkup after repair as well as reusing tanks or pipes previously containing flammable liquid or gas

without thorough purging. Most individual/ human factors could be attributed lack of clear instructions and appropriate training.

- The consequences of the incidents can be worsened due to inadequate preparation of the emergency personnel.

Recommendations have been formulated for different operational modes and industry sectors, separating hydrogen energy applications with the others. Care has been taken to relate the recommendations to the EHSP recommended safety principles. Briefly, the recommends can be summarized as follows:

- The adequate training of personnel is key (SP9). This includes training of new personnel, periodic updated training of existing personnel, external contractors and emergency services.
- Keep the equipment and systems up to date with appropriate surveillance and maintenance. When operational or equipment changes are made, the maintenance/ inspection procedures should also be updated accordingly. Related to this, SP11 will be added to the Safety Principles in the next version of “New guidance document for the Safety Planning and Management in EU hydrogen and fuel cell projects”.
- In terms of system design, it is important to perform process hazard analysis for any new/ updated installations (SP1-10). For systems involving hydrogen, it is important to use materials which are compatible with hydrogen services.
- It should be emphasized again that a key takeaway message is that some accidents might consist of several causal events, which, if occurred separately, might have little consequences; but if these minor events occurred simultaneously, they could still result in extremely serious consequences. Therefore, to ensure plant and personnel safety, it is of critical importance to follow safety principles and operating procedures strictly to avoid any event from occurring.

The readers are also recommended to consult the original event description in HIAD, where there are more details, for specific events of interest. In order to facilitate this, the report frequently quote some examples by listing the event ID number(s) in Chapter 5 “Lessons learnt”.