FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU)

Statistics, lessons learnt and recommendations from the analysis of the Hydrogen Incidents and Accidents Database (HIAD 2.0)

21 September 2021

DOCUMENT HISTORY

Version	Date of release	Description
1	5 October 2020	First draft
2	6 November 2020	Consolidated draft after TF3 and JRC comments
3	16 April 2021	Amendment by EHSP
4	28 June 2021	Amendment and comments by FCH 2 JU
5	25 July 2021	Revised by EHSP
6	7 September 2021	Further revised by EHSP
7	10 September 2021	Amendment and comments by FCH 2 JU
8	21 September 2021	Final revision by EHSP

TABLE OF CONTENTS

1. INTRODUCTION

The Hydrogen Incidents and Accidents Database (HIAD) is an international open communication platform collecting systematic data on hydrogen-related undesired incidents, which was initially developed in the frame of HySafe, an EC co-funded Network of Excellence in the 6th Frame Work Programme by the Joint Research Centre of the European Commission (EC-JRC). It was updated by JRC as HIAD 2.0[1] in 2016 with the support of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU). Since the launch of the European Hydrogen Safety Panel[2] (EHSP) initiative in 2017 by FCH 2 JU, the EHSP has worked closely with JRC to upload additional/new incidents to HIAD 2.0 and analyze them to gather statistics, lessons learnt and recommendations through Task Force 3. The first report to summarise the findings of the analysis was published by FCH 2 JU in September 2019[3].

Since the publication of the first report, the EHSP and JRC have continuously worked together to enlarge HIAD 2.0 by adding newly occurred incidents as well as quality historic incidents which were not previously uploaded to HIAD 2.0. This has facilitated the number of validated incidents in HIAD 2.0 to increase from 272 in 2018 to 593 in March 2021. This number is also dynamic and continues to increase as new incidents are being continuously added by both EHSP and JRC; and validated by JRC. The overall quality of the published incidents has also been improved whenever possible. For example, additional information has been added to some existing incidents.

Since mid-2020, EHSP Task Force TF3 has further analysed the 485 events, which were in the database as of July 2020. For completeness of the statistics, these include the events considered in our first report[3] as well as the newly added/validated events since then. In this process, the EHSP has also re-visited the lessons learnt in the first report to harmonise the approaches of analysis and improve the overall analysis. The analysis has comprehensively covered statistics, lessons learnt and recommendations. The increased number of incidents has also made it viable to extract statistics from the available incidents at the time of the analysis, including previously available incidents. It should be noted that some incidents reported is of low quality therefore it was not included in the statistical analysis.

Following the introduction, the report outlines the source of information for HIAD 2.0, analysis procedures and methodology. This is followed by an overview of the events in HIAD 2.0. The report then describes the statistics, lessons learnt and recommendations that stemmed from this analysis. The report is self-explanatory and hence includes an overview of HIAD 2.0, the analysis procedure, statistics, lesson learnt from this effort as well as the recommendations based on our analysis. Wherever applicable, the recommendations referred to the EHSP identified safety principles.

The readers are also recommended to consult the original event description in HIAD 2.0, 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).

Disclaimer note:

The reader should, therefore, bear in mind, that the statistics, lessons learnt and recommendations documented in the report are based on the available events in HIAD 2.0 and the sources of information.

---

[1] *https://odin.jrc.ec.europa.eu/giada/Main.jsp*

[2] *https://www.fch.europa.eu/page/european-hydrogen-safety-panel*

[3] *https://www.fch.europa.eu/sites/default/files/Assessment%20and%20lessons%20learnt%20from%20HIAD%202.0%20-%20Final%20publishable%20version%20%28version%201.3%29.pdf*

2. DATA COLLECTION, ANALYSIS PROCEDURE AND METHODOLOGY

The data collection is collectively carried out by the EHSP and JRC. The sources for the majority of the historic events in HIAD 2.0 come from some publically release Incidents and Accidents Databases, which are not limited to hydrogen. For events in Europe, this includes the ARIA[4], eMARS[5], MHIDAS[6], which was hosted by UK IChemE but no longer updated. For the historic cases in the US, the sources include CBS news[7], Occupational Safety and Health Administration[8] and National Transportation Safety Board[9]. For Japan, the events were mainly collected from the general National nuclear authorities[10] and RISCAD[11], which generally contained very little information and is no longer maintained. For historic events, some additional cases were also included from those collected by Warwick University from new items online. A small number of events were also collected from scientific publications and other news sources.

With the exception of ARIA (and partially MHIDAS), the others provide accidents reports above a specific severity threshold, and/or focus on specific applications and/or are limited in the time span covered. For example, very probably there is a bias towards stationary, industrial applications. Although this does not hinder our capacity to extract general conclusions, they do influence the percentages of events recorded for different sectors.

EHSP experts are also closely monitoring newly occurred events through news items as well as their international network of contacts. While some of the recently occurred incidents are still under investigation with the final incident report pending or remaining confidential with limited distribution, it is thought the available information, although limited to some extent, can still provide valuable information to inform lessons learnt and recommendations. It should also be noted that these newly occurred incidents are generally closely related to the ongoing worldwide development of hydrogen energy applications.

The “European scale of industrial incidents”[12] and the “Accidentology involving hydrogen”[13] were used to provide some quantification wherever possible on the amount of hydrogen involved, the human, social, environmental and economic consequences. More details are given in the next section.

Figure 1 illustrates the process from data collection, data processing, validation and publishing through to analysis, reporting and final dissemination. Throughout the whole process, EHSP works closely with the JRC and FCH 2 JU.

[4] *https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-data-base/?lang=en#:~:text=What%20is%20ARIA%3F,public%20safety%20or%20the%20environment*

[5] *https://emars.jrc.ec.europa.eu/en/emars/content*

[6] *https://www.icheme.org/media/12093/xiii-paper-05.pdf*

[7] *www.cbsnews.com*

[8] *www.osha.gov*

[9] *www.ntsb.gov*

[10] *https://www.nsr.go.jp/english/*

[11] *www.sanpo.aist-riss.jp*

[12] *https://www.aria.developpement-durable.gouv.fr/wp-content/uploads/2014/08/European-scale-of-acci-dents.pdf*

[13] *https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/SY_hydrogen_GB_2009.pdf*

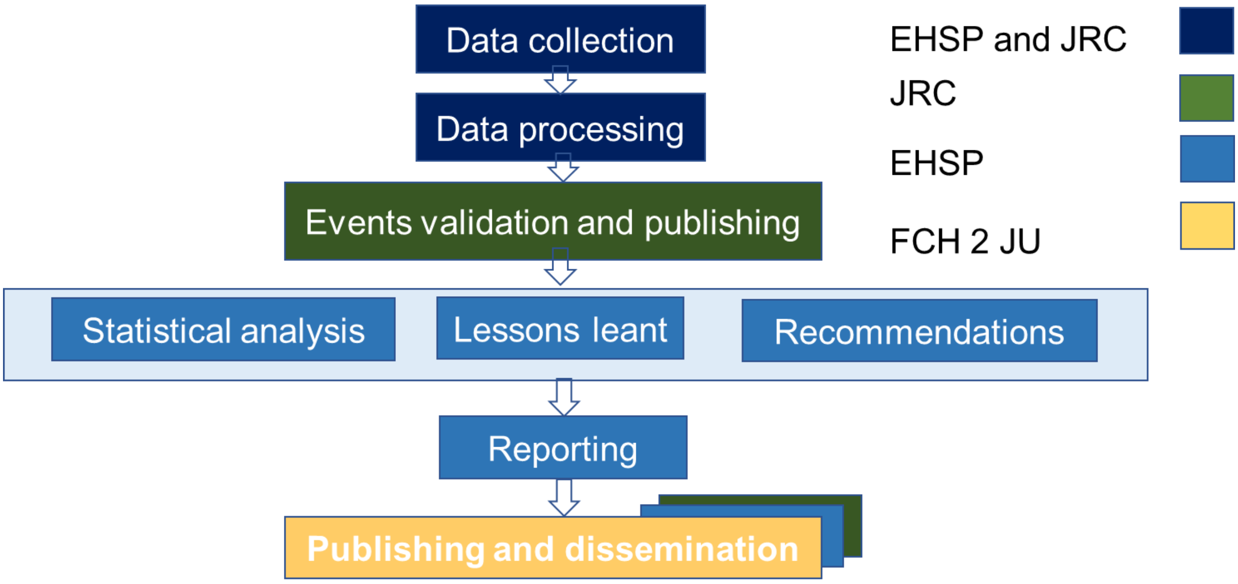

Figure 1: Flow chart of the process from data collection to final publishing and dissemination.

3. OVERVIEW OF THE EVENTS

The incidents contained in HIAD 2.0 are divided into three main categories, i.e. “Event classification”, “Physical consequences” and “Application”. An example of the front-end retrieval page is shown in Figure 2. The screen shot was taken in March 2021 when there were 593 events in the database while the actual event count is a dynamic number as new events are being continuously added, validated and released through the joint efforts of EHSP and JRC. The sources for the events in HIAD 2.0 come from some publically release Incidents and Accidents Databases, which are not limited to hydrogen as well as news items and scientific publications.

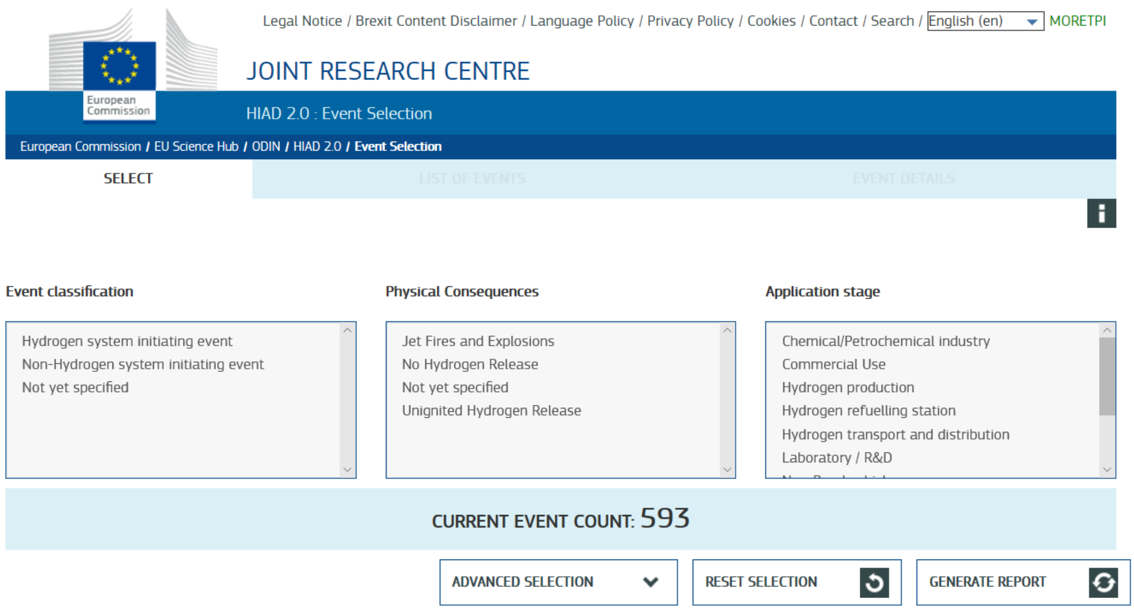

Figure 2: The front-end retrieval page.

The analysis in the current report was conducted for 485 events, which were in the database in July 2020. As shown in Figure 3, most of the incidents included in this analysis occurred in the period from the years 1990s to 2000s. This is merely a reflection that some of the more recent incidents imported by the experts were still in the process of being validated at the time and not included in this report. Figure 4 illustrates the percentage of events in different regions. Almost half of these incidents happened in Europe, while one third occurred in North America. Asia accounts for about a sixth of the incidents, while other regions account for only 3% of the incidents recorded. This is partially because although recently occurred events in hydrogen energy applications are closely monitored and uploaded to HIAD 2.0, sources are scarce concerning historical incidents in Asia countries. The EHSP is currently exploring ways to source reports about historic events across the world to further enlarge the database.

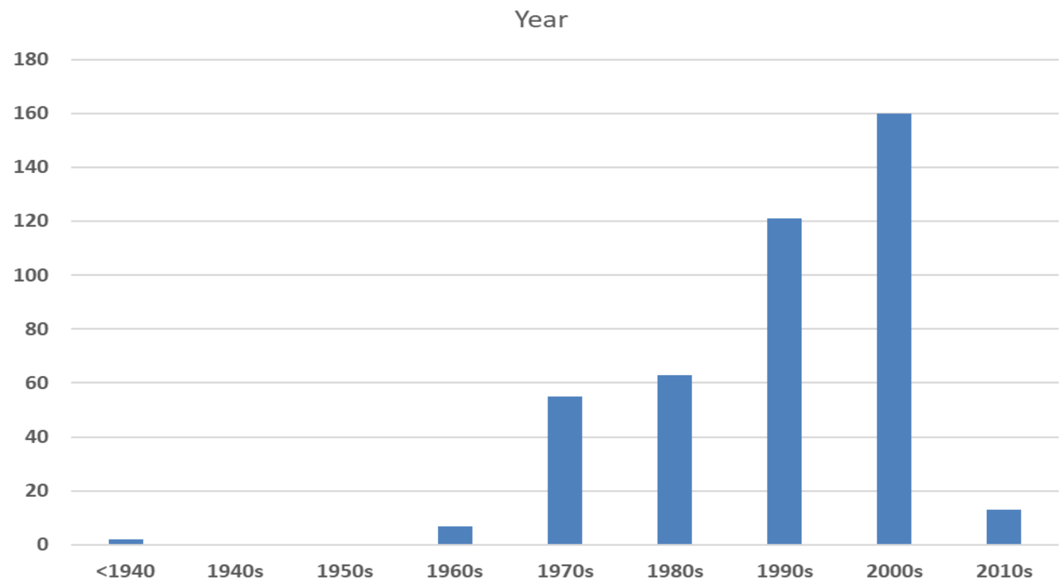

Figure 3: Distribution over time for the events included in the analysis.

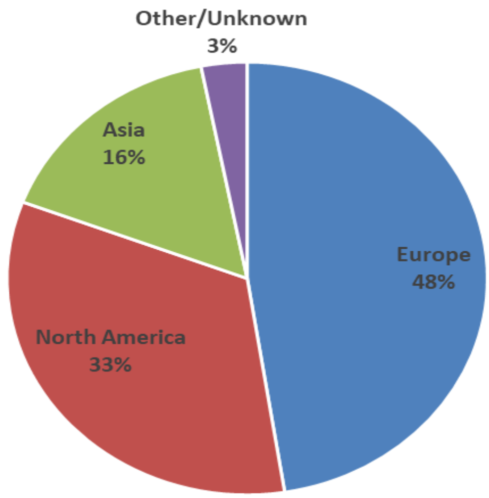

Figure 4: Percentage for different regions in the considered events.

As shown in Figure 2, the first main category "Event classification" is grouped in the following three sub-categories:

- Non-hydrogen system initiating event: event not directly caused by the hydrogen system (e.g. sudden, unintended damage to hydrogen vehicles, installations or plants caused by impact, high voltage, failure of conventional components, etc.)
- Hydrogen system initiating event: event triggered directly by system containing hydrogen (e.g. rupture of hydrogen pipe, valve, tank)
- Not yet specified

Out of these 426 events were considered to be of value for statistical analysis. These include 342 events initiated by hydrogen systems and 84 events initiated by non-hydrogen systems. The outer circle of Figure 5 further illustrates the percentage of events occurred in hydrogen or non-hydrogen related systems. The majority 80% of the incidents considered were initiated by a hydrogen system while the remaining 20% incidents were related to non-hydrogen systems.

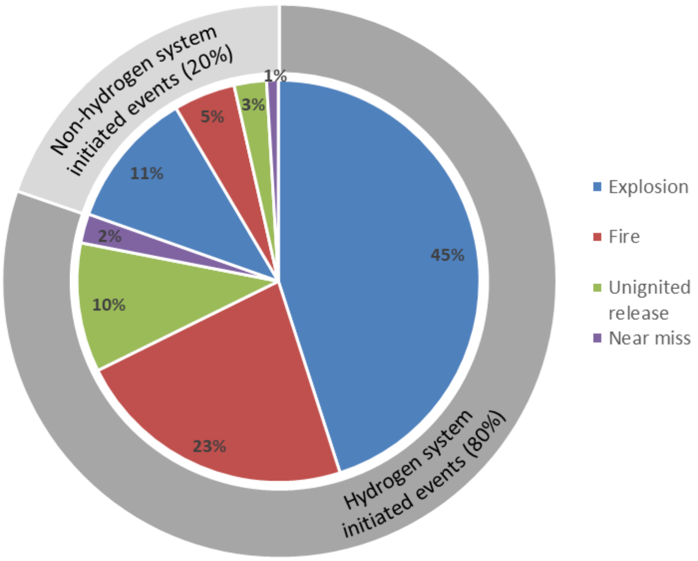

Figure 5: Percentage for those initiated by hydrogen or non-hydrogen systems (outer circle) and those related to different consequences among the considered events (inner circle).

The second main category "Physical consequences" is sub-divided into four sub-categories: explosion, fire, unignited hydrogen release and near miss, which means there was no hydrogen release. It is widely known that hydrogen has a wide flammability range (4-76 % by volume) and it requires little energy to ignite and reaches relatively high laminar flame speeds[14]. Accidentally released hydrogen is prone to be ignited in the presence of an ignition source. The inner circle of Figure *5* provides an overview of the events classified by consequence. Here, the statistics for the consequences related to hydrogen system initiated events and non-hydrogen system initiated events were plotted separately in the inner circle while the combined percentages can be obtained by adding the percentages together. For example, 11% of the events involved explosions initiated in non-hydrogen system while 45% events were explosions initiated in hydrogen systems. Overall, explosions occurred in 56% of the events. It should also be noted that most explosions were followed by fires. Among the events considered, apart from the 3 % near misses and 13 % unignited releases, hydrogen was ignited in 84% of the incidents with 56% involved explosions and 28% of the incidents resulted in hydrogen fires only. The 13% incidents without ignition were attributed to a number of reasons, e.g. the unintended releases being promptly stopped, adequate control of the inventory and ignition sources, etc. The 3% near misses indicates that early detection and prompt action to mitigate any potential releases can still successfully avoid major hydrogen releases. One should also bear in mind that more cases

[14] *https://www.airproducts.com/company/sustainability/safetygrams*

involving unignited releases could have occurred in practice than reported as it is more likely that there were more near misses and unignited releases that were neither detected or reported.

The third main category shown in Figure 2 is the “Application stage”, which has several sub-categories such as hydrogen production, hydrogen transport and distribution, hydrogen refuelling station and road vehicles, etc. Figure 6 illustrates the percentage of events occurred in different industrial sectors. Among the different sectors, the chemical and petrochemical industry has by far the largest share of the incidents with 62%. It is followed by hydrogen transport and distribution with 10% and nuclear power plants with 6%. The other sectors under consideration account for only small shares.

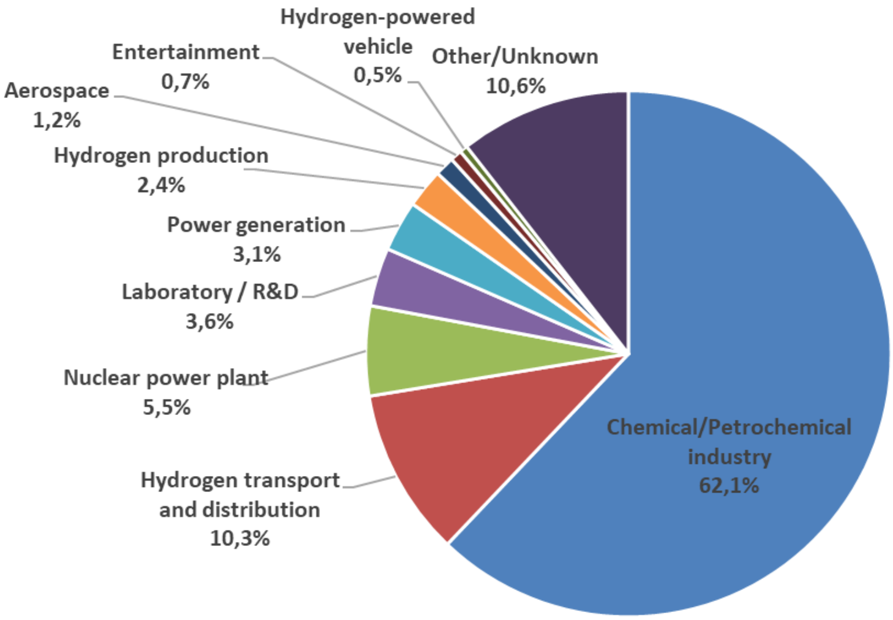

Figure 6: Percentages in different sectors in the considered events.

Table 1 provides an overview of the events classified by sector. The reasons that the total numbers in the two tables are different is because some events were considered to be of relatively little value for statistical analysis and hence not included in Table 1.

Table 1: HIAD 2.0 events classified by sector

Sector	**Number of events by sector**
Chemical/ Petrochemical industry	259
Hydrogen transport and distribution	43
Nuclear power plant	23
Laboratory / R&D	15
Power generation	13
Hydrogen production	10
Aerospace	5
Entertainment	3
Hydrogen-powered vehicle	2
Stationary fuel cell	0
Other/Unknown	44
Total	417

4. STATISTICS

The analysis has comprehensively covered statistics, lessons learnt and recommendations. The increased number of incidents has also made it viable to extract statistics from the available incidents at the time of the analysis, including previously available incidents. It should be noted that some incidents reported is of low quality therefore it was not included in the statistical analysis. As mentioned above, the number of events in HIAD 2.0 is dynamic as new events are being continuously added, validated and published. The analysis conducted in this report is based on the 485 events which were in the database in July 2020. During the individual analysis, the experts were asked to identify whether an event is worth including in the statistics. 426 of these events were considered to be statistically relevant with meaningful information. These events form the basis for the statistical analysis. As the spreadsheet contains several sub-sheets which are dynamically linked to produce some statistics, e.g. timeline, locations, industrial sector, etc. while other statistics, e.g. severity, were manually produced by examining the consolidated spreadsheet for all the 426 incidents.

<u>Statistics on causes and operational mode</u>

Table 2 lists the number of events according to causes. It should be noted that some events had multiple causes and hence counted more than once here.

Table 2: HIAD 2.0 events classified by causes

Cause	Number of events by causes
System design error	126
Material/ manufacturing error	127
Installation error	38
Job factors	98
Individual/ human factors	94
Organization and management factors	158

Figure 7 further illustrates the numbers of events classified by the causes. Some incidents had multiple causes. It is important to note that for nearly 160 events considered, organization and management factors were identified as at least one of the key responsible factors. There were over 120 events for which the root causes were related to system design errors and material/manufacturing errors. Nearly 100 events were related to job factors and the causes of over 90 events were traced back to individual and human factors. Less than 40 events were related to installation error. 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.

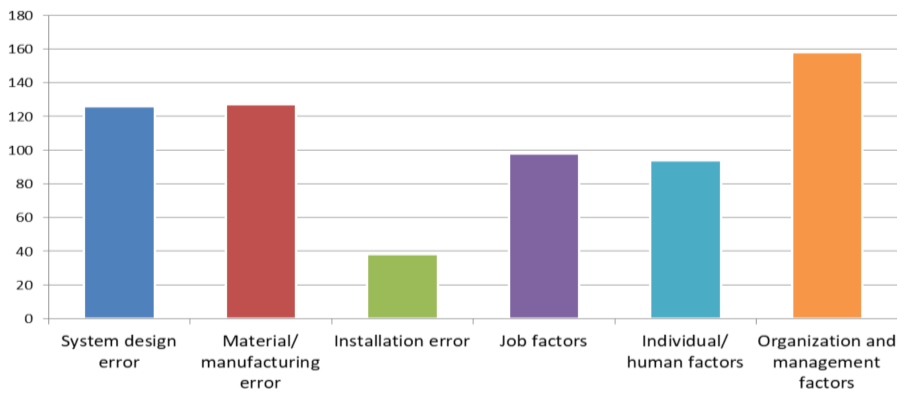

Figure 7: Numbers related to causes of the events (multiple causes per event considered).

Figure 8 shows the statistics about whether the incidents occurred during normal operation or outside. While the majority 70 % incidents occurred during normal operation, 27% occurred outside normal operation during maintenance, special services or immediately after returning from maintenance to normal routine operation.

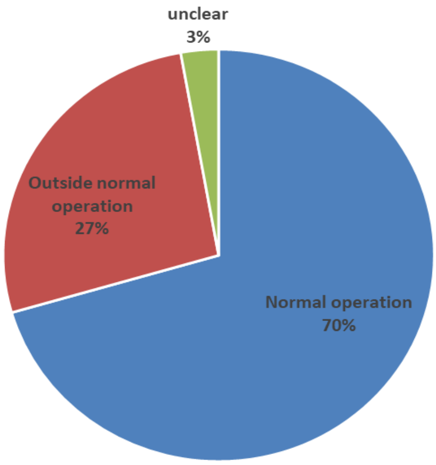

Figure 8: Percentages related to operational mode for the considered events.

Statistics on Severity

The severity of the incidents has been assessed according to the European scale of industrial accidents which is based on the Seveso directive[4] . It was used to classify the consequences according to quantities released or ignited, human and social consequences, and economical consequences. 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. This is based on the assumption of the equivalent TNT method. It should be noted that TNT method is not very representative method for hydrogen explosion and tends to overestimate the consequence. Figure 9**Error! Reference source not found.** shows the variation of the number of incidents based on the quantity of hydrogen released. As can be noticed from the graph majority of the incidents (i.e., 86 %), the quantity of hydrogen released in not reported. As represented by Q1-0 in Fig.9, for 2% of the incidents there was no hydrogen release. In comparison, 3-4% of incidents show more than 500 kg of the hydrogen material released.

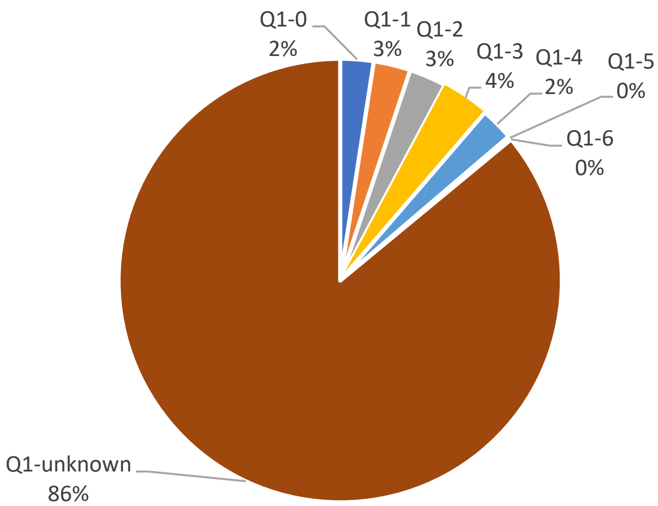

Figure 9: Statistics showing the percentage of events classified by quantity of hydrogen.

The labels in the figure are defined according to the European severity scale parameters specified in European scale of industrial incidents [12].

Quantities of dangerous substances		1	2	3	4	5	6
Q1	Quantity Q of substance actually lost or released in relation to the "Seveso" threshold *	Q < 0.1%	0.1% ≤ Q < 1%	1% ≤ Q < 10%	10% ≤ Q < 100%	1 to 10 times the threshold	≥ 10 times the threshold

For the classification of human and social consequences the number of fatalities (H3) or injured (major (H4) or minor (H5)) persons has been applied. **Error! Reference source not found.** shows that 39% incidents did not lead to any fatality, while 16% and 5% of incidents has led to fatalities of up to 5 people. Several incidents, e.g. incidents IDs10, 12, 21, 611 and 698, led to more than 20 deaths each. Most of the fatalities in these incidents were caused by the explosion of hydrogen-air gas cloud. There are 29% of the incidents for which the collected information is insufficient to conclude whether the incidents resulted in any deaths.

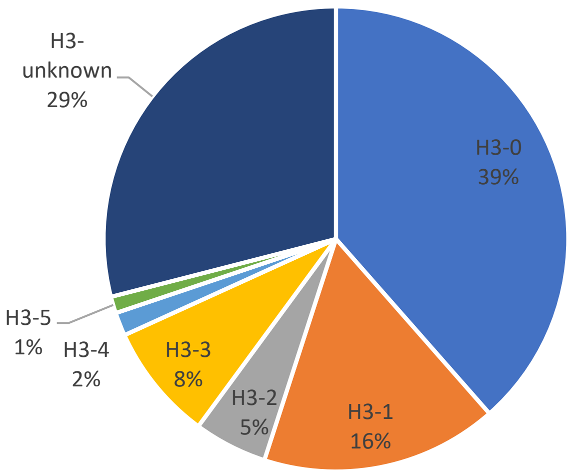

Figure 10: Statistics showing the number of incidents reported with fatality.

The labels in the figure are defined according to the European severity scale parameters specified in European scale of industrial incidents [12].

Human and social consequences		1	2	3	4	5	6
H3	Total number of deaths: including - employees - external rescue personnel - persons of the public	- - - -	1 1 - -	2 – 5 2 – 5 1 -	6 – 19 6 – 19 2 – 5 1	20 – 49 20 – 49 6 – 19 2 – 5	≥ 50 ≥ 50 ≥ 20 ≥ 6

Figure 11 shows that 36% of the incidents reported no major injury while Figure 12 indicates that 64% of the incidents resulted in only minor injuries. In contrast, 13% and 5% of the considered incidents reported significant injuries of up to 5 people and minor injuries of up to 19 people. There are up to 30% of the incidents, the collected information was insufficient to decide whether the incidents led to any injury.

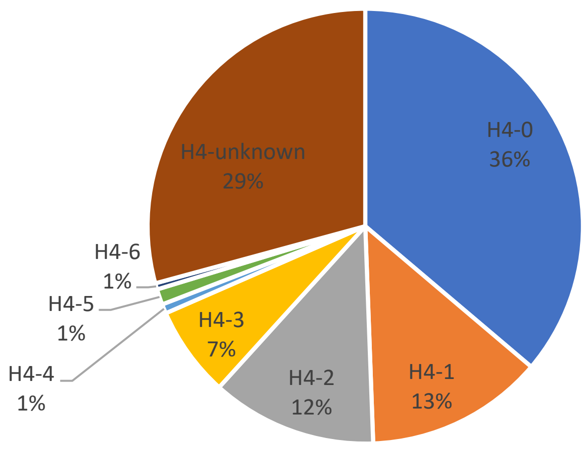

Figure 11: Statistics showing the number of incidents reported with significant injury.

The labels in the figure are defined according to the European severity scale parameters specified in European scale of industrial incidents [12].

Human and social consequences		1	2	3	4	5	6
H4	Total number of injured with hospitalisation ≥ 24 hours:	1	2 – 5	6 – 19	20 – 49	50 – 199	≥ 200
	including - employees	1	2 – 5	6 – 19	20 – 49	50 – 199	≥ 200
	- external rescue personnel	1	2 – 5	6 – 19	20 – 49	50 – 199	≥ 200
	- persons of the public	-	-	1 – 5	6 – 19	20 – 49	≥ 50

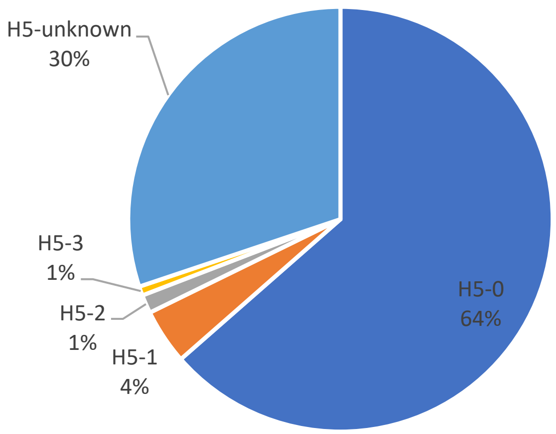

Figure 12: Statics showing the number of incidents reported with minor injury.

The labels in the figure are defined according to the European severity scale parameters specified in European scale of industrial incidents [12].

Human and social consequences		1	2	3	4	5	6
H5	Total number of slightly injured cared for on site or with hospitalisation < 24 hours:	1 – 5	6 – 19	20 – 49	50 – 199	200 – 999	≥ 1,000
	including - employees	1 – 5	6 – 19	20 – 49	50 – 199	200 – 999	≥ 1,000
	- external rescue personnel	1 – 5	6 – 19	20 – 49	50 – 199	200 – 999	≥ 1,000
	- persons of the public	-	1 – 5	6 – 19	20 – 49	50 – 199	≥ 200

Statistics on Safety Principle

In 2019, the EHSP published a guidance document for "SAFETY PLANNING FOR HYDROGEN AND FUEL CELL PROJECTS"[15], in which the EHSP experts extracted ten safety principles from the actions required to prevent an escalation of a prototypical hydrogen accident. The derived Safety Principles (SP), as listed in Table 3, state simple objectives, being widely understandable and acting as preventive barriers or at least as risk reducing measures on the various elements of the chain of events.

Table 3: The Safety Principles (SP)

Number	Safety Principle	Explosion/ Protection Tier
1	Limit hydrogen inventories, especially indoors, to what is strictly necessary	1st 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	2nd 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	3rd 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	

The 426 incidents in HIAD 2.0 considered by the experts to be of statistical value as of July 2020 were individually analysed by the EHSP based on the available incident information. The recommendations were provided against each incident based on Safety Principles (SP1-SP10). However, it was noted that for some events, the safety principle suggested by individual expert is the best guess based on the information available from HIAD 2.0 database. The EHSP plans to devise a consistent methodology to determine the relevance of the incidents to specific safety principle in 2021.

During the analysis, it was found that for various incidents, a common cause was because the design of hydrogen system or the selection of materials which were not compatible with hydrogen services. It is hence proposed to add a new safety principle SP0 to account for poor design of hydrogen system

[15]*https://www.fch.europa.eu/sites/default/files/Safety_Planning_for_Hydrogen_and_Fuel_Cell_Projects_Release1p31_20190705.pdf*

and material selection. While this proposition has yet to be adapted by the Task Force 1 of the EHSP, it is not included in the current analysis for clarity.

The results of the analysis are shown in Figure 13. Out of the 426 incidents considered, the major contributing factors were from SP9 (26 %) and SP10 (15 %). The data clearly shows that lack of training of operators/plant personnel and lack of understanding of hydrogen hazards is a key area which need further improvement. In addition, lack of a system to report near misses/incidents and apply learning from it for further development of a safety plan is another area which has contributed these incidents.

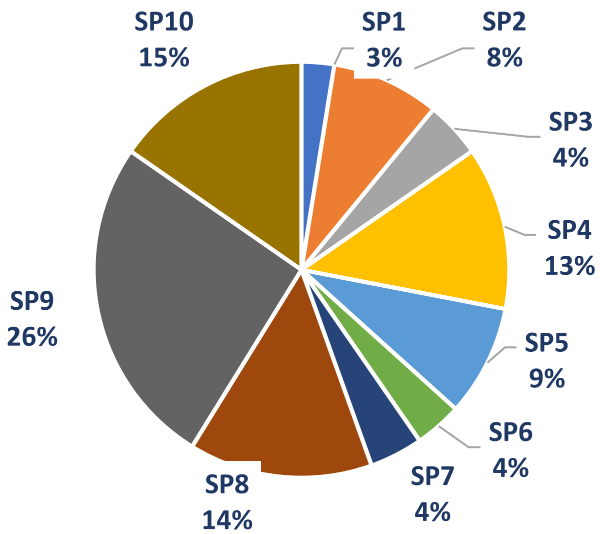

Figure 13: Statistics showing the number of incidents reported with different SP listed in Table 3.

As a next step, it is further checked to see whether statistics related to the safety principles follow any trends with respect to year of incident. Figure 14 shows that the lack of training, reporting system and poor design of the system has contributed to the majority of the incidents regardless of any span of a year (i.e., less than 1990, 1990-2000, 2000-2010 and 2010-2020). It is to be noted that the number of incidents reported in the HIAD 2.0 database is limited in 2020; hence incidents in 2020 must be excluded for the statistics; however, it is included for completeness. Overall, the trend shows the importance of training of personnel and incident reporting system.

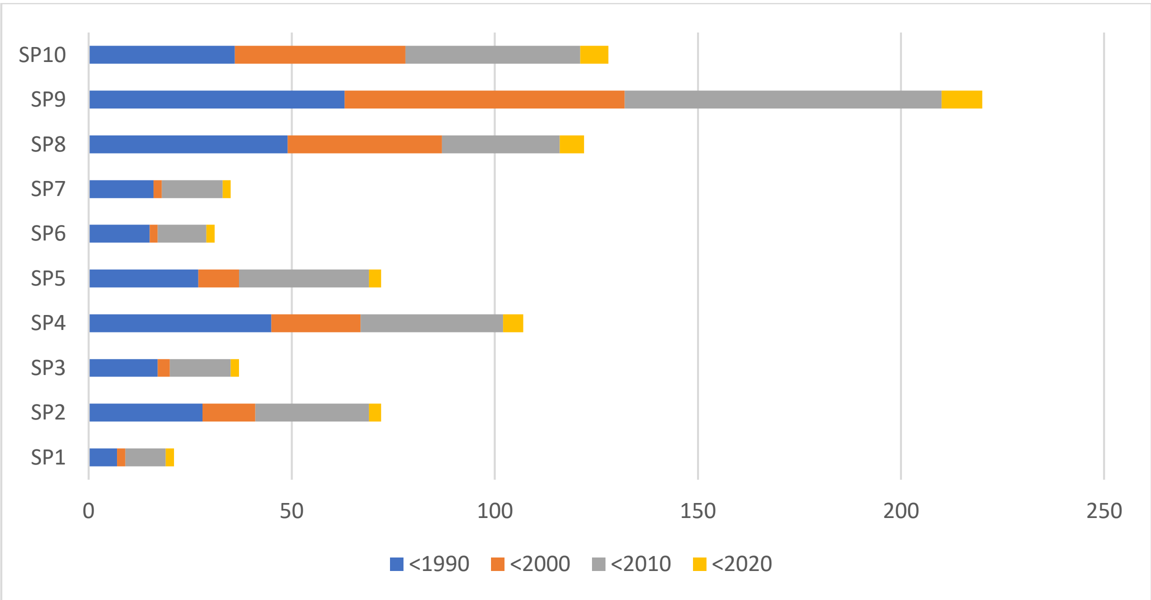

Figure 14: Variation of recommended SP (listed Table 3) with reported year of incident.

5. LESSONS LEARNT

Since mid-2020, EHSP Task Force TF3 has further analysed the 485 events, which were in the database as of July 2020. For completeness of the statistics, these include the events considered in our first report[3] as well as the newly added/validated events since then. In this process, the EHSP has also re-visited the lessons learnt in the first report to harmonise the approaches of analysis and improve the overall analysis. This section is, hence, devoted to lessons distilled from the 485 events.

Despite that the lessons learnt from each event are specific and particular to the event conditions itself, this section aims to provide some common aspects gathered from the lessons learnt compiled in the individual reports of the experts involved.

In order to facilitate the reading, the lessons learnt and recommendations provided in this section are grouped into several sub-sections according to their causes. Four main categories, as shown in Table 5, have been defined. Two categories are related to the system in terms of its design, manufacturing, installation and modification. One category is related to operator errors, which have been further classified into three sub-categories: job factors, individual/human factors and organisation and management factors. In each category, the specific lessons learnt are described and some significant incidents are highlighted. Some examples linked to specific lessons learnt are mentioned and those events which warrants special attention by those in similar operations are highlighted. The last category is related to first responders.

The overarching lessons learnt is that incidents might consist of several causal events that, if occurred separately, might have little consequences; but if these minor events occurred simultaneously, they could still result in serious consequences. Some incidents were caused by multiple reasons. To reinforce lessons learnt from cascading effects, some relevant incidents were highlighted in the Section 5.5.

The report is based on the analysis of the incidents description in HIAD 2.0. Although some key information relevant to the description of lessons learnt was extracted, the readers are recommended to consult the original event description in HIAD 2.0, where there are more details for specific incidents.

Table 5: 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 H_2 safety and accident scenarios
	Corrosion related	Venting system	Safety device during maintenance	Inadequate training of H_2 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 H_2 generation	Verification of design and operation conditions	Procedures for fast isolation of the release sources	Lack of sufficient evidence gathering
	H_2 generation due to malfunction		Insufficient check after repair	Emergency procedure not followed	Guidance about lifetime of critical components	Extinguishing fire before H_2 release stopping
	Venting		Insufficient purging Before re-using	Guidance to prevent unwanted H_2 generation	Explosivity control before maintenance	Efficient safety crew
	H_2 accumulation			Handover between shift and day staff	Distinction between emergency and operating alarms	
	2nd order redundancy on critical systems			Ignorance about volatile pressure of hydrocarbons in tanks		
				workplace safety violation		

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.

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.

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.

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.

Corrosion related

Considerable amount 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.

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 fertilizers 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.

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.

Equipment factor

The explosion and fire in event ID609 was 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.

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 plan 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 resulted in hydrogen generation could help to prevent such incidents from occurring.

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 enclosed; 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 built up of the leaked hydrogen and direct any leaked hydrogen away from the enclosure to avoid reaching the ignition source.

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.

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).

Highlighted incidents 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 accidents 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.

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 reference[16].

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.

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.

---

[16] *ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems.*

- 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.
- 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.

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

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.

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 m^3 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.

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 classification[17] 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 2.0 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.

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.

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.

[17] *https://www.hse.gov.uk/humanfactors/topics/humanfail.html*

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.

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 H_2S applications. Appropriate training and enforcement of compliance with safety practice and appropriate procedures can help to reduce incidents due to individual/ human factors.

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.

Training and procedures to avoid accidental generation of hydrogen

In Section 5.1, 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.

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.

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

Lessons from event IDs531, 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.

Highlighted incidents with good lessons to be learnt for relevant operators

Event ID477, 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 m^3 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 constructer 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 necessities 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.

5.3.2 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) and aware of the need to avoid routes in the vicinity of buildings and people during transportation, event ID719.
- 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.

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.

5.3.3 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.

<u>Highlighted incidents with good lessons to be learnt for relevant operators</u>

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 Guide[18].

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. Quick 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 on the basis of crucial and relevant technical information. The 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.

[18] *https://hyresponder.eu/e-platform/european-emergency-response-guide/*

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.

5.5 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 ID653 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 ID598 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.

6. RECOMMENDATIONS

This section is dedicated to recommendations distilled from the incidents added to HIAD 2.0 databases since the release of our previous report in 2019. It aims at providing the general recommendations applicable for various incidents recorded in the HIAD 2.0 database. 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.

In formulating the recommendations, links are made to the relevant Safety Principles wherever possible. Rather than following the same structure and sub-categories in the previous chapter “lessons learnt”, the experts considered it more appropriate to formulate recommendations according to optional mode and industry sectors to render it easier to follow by different readers. A dedicated section is devoted to recommendations on human errors. Table 6 provides a glance about how the recommendations are organised while the actual recommendations are described under each relevant sub-heading.

Table 6: Structure of recommendations at a glance

Recommendations	***Operational mode***		
	Industrial sectors	Hydrogen energy	H_2 transport and distribution
			H_2 powered vehicle
			Laboratory / R&D
			Power generation
			Entertainment
		Other industrial sectors	Nuclear
			Aerospace
			Chemical/ petrochemical sector
	Other sectors		
	Human errors		

6.1 Recommendations for different operational modes

Approximately two thirds of the incidents considered happened during normal operations, while around one third took place outside normal operations, for example during testing, maintenance, starting after maintenance, etc. An analysis of the incidents provided the following recommendations:

- Adequate training of personnel is key (SP9): this is of utmost importance. As shown in the statistical analysis illustrated in Figure 8, 70% of the considered incidents occurred during normal operation. Insufficient or inadequate training of personnel was detected in 23% of the incidents analyzed. Periodic training of personnel, new personnel and senior one is crucial for keeping the skills and getting used to following the procedures.
- Both passive and active safety measures should be given a crucial role. At least 19% of the incidents considered involved lack of sufficient and adequate safety devices or passive measures (SP7, SP8). Leak detection (SP4) and ATEX zoning (SP3, SP5) should be applied to reduce the opportunities for incidents.
- It is necessary to keep the equipment and systems up to date and clean with appropriate surveillance and maintenance. Updating maintenance procedures to consider changes is crucial. 13% of the incidents analyzed showed problems related to lack of maintenance and surveillance (SP8).

A final recommendation is to perform a throughout risk/ hazards assessment during the design phase and before any process or equipment change. More than 10% of the incidents analyzed in this exercise have shown that wrong design had a critical role in the event. Although this recommendation is difficult to implement during the operation mode, it can be an effective means to prevent incidents through inherently safer design.

6.2 Recommendations for different industry sectors

6.2.1 Hydrogen energy applications

The ultimate target of the EHSP is to ensure safety for the FCH 2 JU program including projects but also to facilitate the large deployment of hydrogen energy applications with adequate safety considerations. This section is focused on specific hydrogen applications of interest for the fuel cell and hydrogen community. These are the high-level preliminary recommendations based on the current analysis of the 485 events, and they are subject to further improvement following analysis of the newly added events in the coming years.

6.2.1.1 Hydrogen transport and distribution

Among the 485 incidents considered, 39 incidents were linked with hydrogen transport and distribution representing 10 unignited hydrogen releases and one release of liquid hydrogen, 12 explosions and 13 fires, only 4 near-misses were found.

An important recommendation, which were relevant to almost all incidents, is that the safety training of the personnel should be enforced (SP9). Learning from incidents and near misses in the past (SP10) is essential to avoid new incidents.

Recommendations to reduce traffic incidents

Traffic incidents including rollover and crashing with other vehicles was the cause of almost all near-misses, three incidents with unignited hydrogen release and two fire incidents. Based on the available information it is recommended to:

- Hire certified drivers and/or perform the corresponding safety training regularly. Special consideration for training should be given for liquid hydrogen trailers (SP9), which is relatively new to many drivers.
- Drivers also should take proper rest in line with the local regulations and recommendations for the maximum driving distance and time. An example can be found in reference[19] for the EU.

The cause of several other incidents was related to operational fault including faulty connections on liquid hydrogen venting system, improper handling of liquid hydrogen transfer, rupture of connecting pipe during loading of bottles rack, hydrogen gas leakage from a cylinders fall during the transportation, inappropriate hydrogen transfer, inappropriate maintenance or installation error. The recommendations based on the analysis of these incidents include:

- Maintenance should be performed by qualified personnel and should be verified/ certified.
- Installation of extra safety barriers: such as pressure & temperature, concentration sensors, break away devices, installation of the second strap for cylinder hold (SP2, SP8).

Recommendations to improve system design

System design errors caused fire and explosions in several traffic incidents. It is typically related to the selection of wrong materials which are not compatible with hydrogen or poor welding, unexpected chemical reactions and unsafe design. The following recommendations are made in consideration of these:

- Perform Process Hazard Analysis for the new/ updated installations (SP1-10);
- Use materials which are compatible with hydrogen services. It should be noted that in certain incidents, this resulted in the need to change standards/ codes for pressure vessel (to be added as SP0 to the list of Safety Principles); and
- Install high fidelity leak detection and other extra mitigation barriers (SP4, SP8).

[19] *https://ec.europa.eu/transport/modes/road/social_provisions/driving_time_en#:~:text=Total%20weekly%20driving%20time%20may,maximum%20three%20times%20a%20week.*

Recommendations related to material failure

The failure of fittings, valves, tanks, rupture disc, venting system and even pipeline due to corrosion can lead to fire and explosions. The following general recommendations can be given in relation to prevent such failure:

- Regular check and maintenance and inspections should be carried out (SP10).
- The operator should consider the installation of mitigation barriers such as hydrogen sensors, pressure sensors, so that any hydrogen leak can be detected promptly for mitigation measures to be implemented (SP4, SP8).
- Take all possible measures to avoid any ignition sources to come close to the leaked hydrogen (SP3, SP5); and
- Ensure adequate functioning of hydrogen venting devices.

6.2.1.2 Hydrogen-powered vehicle

A special interest in hydrogen safety represents incidents occurred with hydrogen-powered vehicle. Currently there is only one declared incident in HIAD 2.0. It was a near-miss concerning an experimental hydrogen powered vehicle. This near-miss demonstrates that the operators avoided more serious incidents by following two safety principles, which are recommended for all sectors with hydrogen-powered vehicles:

- The corresponding staff should be trained and educated about hydrogen safety (SP9).
- All near-misses should be declared (SP10).

6.2.1.3 Laboratory / R&D

Attention must be paid to R&D installations and laboratories involving hydrogen. Among the incidents considered, thirteen were reported by Laboratory/ R&D sector. Among them, only two occurred outside normal operation and explosion was the most frequent consequence.

Recommendations to minimize the occurrence of such incidents in laboratory/ R&D installations that handle hydrogen can be grouped in the following three categories:

- Perform an exhaustive risk analysis for each specific activity to identify safety measures required, including leak detection. Inadequate risk assessment have led to several explosions incidents in HIAD 2.0 (SP1-10).
- Periodically update safety procedures and provide adequate training for personnel involved to follow them. Lack of training and/or changes in procedures have led to some severe consequences involving explosion (SP9).
- Carry out periodic surveillance and maintenance of equipment, especially safety devices (valves) and testing protocols. Incidents causing fire and/ or explosion were due to lack of adequate maintenance in safety valves, electrolyzer, hydrogen cylinder (SP8).

6.2.1.4 Power generation

Power generation plants represent a sector of interest for the hydrogen community as they accumulate many years of operation and the occurrence of incidents involving hydrogen can provide a basis for recommendations. Twelve incidents involving hydrogen in the power generation sector were found among the incidents considered in this analysis. Only two out of the 12 incidents occurred outside normal operations. The main recommendations from the incidents analyzed can be grouped in two categories:

- Perform periodic and frequent surveillance and maintenance of equipment. Material failure and malfunctioning of systems can lead to hydrogen leak and explosion.

- Continuous updating of testing procedures, including ATEX requirements, especially in case of changes (management of change approach). Several incidents involving serious fire and explosion occurred due to a deficient hazard assessment and deficient testing protocol (SP1-10).

6.2.1.5 Entertainment

It is recommended to stop using hydrogen for entertainment, e.g. hydrogen filled balloons. Even if they are used, do not transport them in closed containers (SP1). Past incidents demonstrated that the leakage of hydrogen is possible from balloons. Filling of balloons by hydrogen in public areas is also of high risk. Incidents involving hydrogen balloons can lead to serious consequences involving fire and explosions.

It is recommended to use helium instead of hydrogen for balloons for entertainment. However, adults should verify the children will not play with helium contained in the balloons to avoid a potential risk of asphyxia.

6.2.2 Other industrial sectors

6.2.2.1 Nuclear sector

Main recommendations for the nuclear sector are based on the analysis of 26 incidents involving the production and release of hydrogen which lead to fire or explosion, occurred not necessarily in the nuclear part of the installation:

- Adequate training and safety procedures (SP9-SP10) were found to play a critical role. Six out of the 26 incidents reviewed (23%) took place outside normal operation. For all of them, the lack of training was found to be the most significant cause of the incident. When looking at incidents occurred during normal operation, the percentage was found to be as high as 60%.
- The installation of hydrogen leak detection and monitoring systems (SP4) is highly recommended in enclosed spaces.
- Adequate ventilation is recommended in areas or spaces where hydrogen is handled. Several incidents were related to lack of hydrogen leak detectors.
- Avoid/ minimize the formation or accumulation of radiolytic gases, which may induce electrolysis and formation of hydrogen and accumulation of explosive mixtures (SP2).

6.2.2.2 Aerospace

Aerospace is one of the first industrial sectors for hydrogen application. The 6 incidents in HIAD 2.0 involved space shuttles as well as aerospace applications with 1 unignited hydrogen release and 5 explosion fires. Two of these incidents occurred outside normal operations. Even when excluding “Zepplin” catastrophe, the severity level of other accidents was high, e.g. 7 fatalities in one shuttle explosion. Recommendations to minimize the occurrence of such incidents include:

- Any changes on the installation should be followed by an update of the safety procedures, relevant documentations should be available at any relevant time and communicated to the whole team.
- Provide adequate training for personnel (SP9).
- Hydrogen compatible materials should be used (SP0). The design of the installation should be compatible with hydrogen services.
- Adequate ventilation should be in place to prevent the formation of a flammable cloud (SP2).

- Hydrogen leak detection should be installed (SP4).
- ATEX zoning should be verified (SP3,5).
- Carry out periodic/ frequent maintenance and inspections. Several incidents involving explosions were due to lack of adequate maintenance and appropriate communication of the information (SP8).

6.2.2.3 Chemical/ petrochemical sector

Chemical/ petrochemical sector represents more than 60% of the incidents collected in HIAD 2.0 and analyzed in this report. Recommendations are grouped according to the safety principles, highlighting those aspects with greater occurrence rates according to the statistics shown in Figure 5.

It is worth mentioning that very few incidents can be associated to a unique cause and most of the cases analyzed involved a combination of technical failure, and/or design and human errors. As such, one single incident can lead to several recommendations and on the contrary, several incidents can be the basis for one specific recommendation. For example, in 26% of the incidents analyzed, insufficient hydrogen leak and fire detection systems and/ or passive safety countermeasures were identified (SP4/ SP8). In the following, a comprehensive range of recommendations are grouped into several categories:

Recommendation related to reduce H2 leaks leading to fire/ explosion

- Early identification of leaks with hydrogen detection devices and process parameters (e.g. pressure, temperature) deviations with sensors, alarms and availability of automatic shutdown systems controlled by leak or fire detection is of crucial importance (SP4). Lack of sensors or deficiencies in ATEX zoning has resulted in some of the most serious incidents in different types of equipment including compressors, process unit such as reactors or tanks and pipelines, etc.
- Identification and continuous monitoring/ surveillance of critical process parameters (pressure, temperature, hydrogen concentration) is highly recommended to prevent the occurrence of initiating events such as fatigue corrosion, thermal stress, overpressure or fouling/blockage.
- Periodic inspections are essential to prevent incidents in equipment already repaired (SP8).
- Always use an inert gas during testing and cleaning of equipment (SP8).

Recommendation related to reduce the impact of consequences in case of fire/ explosion

Provide adequate protective walls, mitigation measures and safety distances to avoid/minimize domino effects (SP8).

Recommendations for specific process equipment: reactors, high pressure hydrogen storage tanks and compressors, etc.

Hydrodesulphurization units, hydrocracking reactors or hydrogen storage tanks require special attention to minimize incidents in chemical/ petrochemical installations. Despite taking into account the particular case, some general recommendations can be drawn from the analysis of the incidents:

- Adequate design is critical, equipment must correspond to the process requirements and construction material must be compatible with hydrogen and other streams processed.
- Mitigation measures must be adequately designed. Sufficient safety distances need to be implemented.

- Periodic inspection, maintenance, cleaning and other outside normal operation activities have to be performed under inert atmosphere.
- ATEX zoning is essential, for example compressors are not always considered within the classified safety areas.

<u>Specific recommendations for pipelines</u>

- Periodic inspection of pipelines and connections is essential for an early identification of problems such as corrosion or embrittlement.
- Regular maintenance of equipment (seals, flanges, elbows, etc.) and monitoring of process parameters including the availability of adequate shutdown systems is also crucial to reduce leaks.

6.3 Other sectors

Other sectors represent 6% of the events included in this analysis. They cover different industrial applications such as furnaces, steel plants, transportation of iron chloride, pulp and paper industry, etc. These included 3 hydrogen releases (including one liquid hydrogen leakage), 17 explosions and 12 fires. The affected equipment included exhaust systems, pipelines, tanks, cylinders, compressors, furnaces and turbines, etc. The analysis led to the following recommendations:

- Use equipment of standard design fully adapted to the application.
- Provide written procedures for inspection/ revision of the inspection plan, installation and maintenance, communicate these procedures to staff clearly (SP9).
- Perform risk assessment (SP2) and develop special procedures for tank inerting.
- Provide adequate and periodic training for the personnel involved to ensure that they have the required skills and knowledge (SP9).
- Only use materials compatible with hydrogen used (SP4). Use only adequate storage conditions.
- Use ventilation to avoid formation of flammable cloud (SP2) and leakage detection systems (SP4).
- In specific cases with a possible stagnant zone in pipes, it is recommended to avoid such zones in the installation design (SP2) or to monitor hydrogen concentration within the zones if their complete elimination is not possible (SP4).
- Inert the gas line before starting maintenance (SP2). The sensors should be appropriately installed and checked. Conditions of pipelines, tanks and other equipment should be regularly checked corresponding audit and maintenance should be performed.

6.4 Recommendations concerning human errors

In 29% of the incidents analyzed, the event was due to human errors and to a lack of safety culture and training (SP9/ SP10). These included more than 140 events, which highlight the importance of hydrogen safety training (SP9). Training is essential as design fault (including material selection), incorrect installation, job factor, individual factors, organization and management factors were found to be responsible for many incidents. The training aspect (SP9) was also found to be associated with other SPs (most frequently with SP2, SP4, SP8 and SP10) in the considered events.

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

- Train staff for safe operational management about the following specific aspects:

    - criticality of using only ATEX equipment in the “proximity” of a hydrogen venting
    - the connection procedures of gas cylinders,
    - importance of pre –start safety checks, and
    - check pressure vessels regularly and make sure they are operated under permitted conditions only, etc.

- Establish effective permitting system for the control of maintenance activities. The personnel should be certified or should have a permit-to-work.
- Train staff to follow the safety protocol(s).
- Perform comprehensive training about safety-critical areas and improve additional trainings in the following aspects:
    - risks related to pressure equipment including start-up, inspection, maintenance and shut-down operations,
    - tightening of stuffing box packing,
    - other substances which may be mixed with hydrogen under operational or/ and accidental conditions, and
    - maintenance and problem identification search, etc.
- Operators should be trained to follow special procedures allowing them to avoid extreme operational changes (operations manual should define what kind of gradients are acceptable) or competently bring various technical apparatus in safe modus by smooth and controlled operations.
- Personnel (internal and external/ subcontractors working with hydrogen equipment) should be trained to any changes in the procedures for start-up, inspection, maintenance, shut-down and emergency plans.
- The training needs to be stringent and repeated at regular intervals. The responsible personnel for the plant operations needs to be updated even for operations considered "routine", emphasizing the necessity of following the rule.
- In accordance with the lessons learnt for the emergence services, the staff training should also be carried out in collaboration with relevant external emergency services. The interaction with emergency services should start with risk management based on risk analysis so that potential risks can be excluded as much as possible. This should then be followed by the prevention of accidents at the installation and plant. In addition to frequent joint training of emergency procedures in the form of disaster drills, equipping the emergency services with crucial and prior rescue information such as intervention plans and procedures as well as emergency and evacuation plans is the key to success.

SP10 recommends to declare the accidents/incidents and near-misses and to include the associated lessons learned to the safety plan. It was referred to in 85 events. However, this information should be correctly communicated to the employers. Hence, SP10 is closely linked with SP9. The general recommendations which are useful for different applications are highlighted below:

- Perform frequent audit, including random unexpected inspections and update the start-up, inspection, operation, maintenance and shut-down procedures. These updates can be due to the changes in the installation or/ and operation conditions and due to previous accidents/ incidents/ near-misses.
- The operating procedures have to be appropriate and compatible to all aspects of conditions.
- The equipment must be compliant with the requirements of the operator including the material choice for the equipment.

- Any deviations on working procedures should only be allowed after thorough evaluation.
- Any deviations on process changes such as changes in operating temperature should only be allowed after thorough evaluation. The safe operating window of process parameters (pressure, temperature, flow rate...) must be determined and documented.
- Updated safety management procedure should be correctly written by the corresponding/ responsible person and verified, the responsible person should be present during the preparation and the corresponding maintenance work.
- Any repair /maintenance works should be supervised during delicate phases.
- Any changes in procedures must be clearly communicated to employees including sub-contractors.
- The feedback from past events (accidents/ incidents/ near-misses) must be taken into account.

7. CONCLUDING REMARKS

The joint effort between EHSP and the JRC have facilitated the continuous enlargement and overall enhancement of HIAD 2.0. Newly occurred events as well as historic events which were previously not in the database are being continuously identified and added. At the time of writing the report, there were 577 events in the database while actual event count is a dynamic number as new events are being continuously added, validated and released in the public version of HIAD 2.0.

EHSP Task Force TF3 has analysed 485 incidents which were in the database in July 2020. The analysis has comprehensively covered statistics, lessons learnt and recommendations. The statistics has been gathered in terms of industrial sectors, systems (hydrogen or non-hydrogen systems initiated events), consequences, operational mode, cause, severity in terms of amount of hydrogen involved and levels of human consequences. In the analysis, the experts were also asked to link the relevance of event with the 10 safety principles formulated by the EHSP, the relevance to the safety principles is hence also included in the statistics. Economic and environmental consequences were considered but the events which included such information were just too small to derive meaningful statistics.

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.

Typical examples of design related lessons learnt include lack of precaution during the design stage to limit hydrogen inventory and lack of protection of vessels against thermal attacks. Some weak points which were prone to incidents were also identified including gauge glass for liquid tank level monitoring, flange connections and welding joints. 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.

Only some limited lessons learnt could be gather in relation to first responders due to the lack of such information in the event description. It is hence important for the community to provide this aspect some consideration when reporting events.

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. Overarchingly, the adequate training of personnel is key (SP9). This includes training of new personnel as well as periodic updated training of existing personnel. In accordance with the lessons learnt for the emergence services, the staff training should also be carried out for relevant external emergency services to help ensure their awareness of crucial and prior rescue information such as intervention plans, intervention procedures, emergency and evacuation plans.

Both passive and active safety measures should be appropriately considered, including using adequate safety devices or passive protection measures (SP7, SP8) as well as implementing leak detection (SP4) and ATEX zoning (SP3, SP5) to improve safety. The importance to install reliable leak detection and other extra mitigation barriers (SP4, SP8) for critical systems is highly recommended.

Furthermore, it is necessary to 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. 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. In some incidents, such problem resulted in the need to change standards and codes for pressure vessels. Based on this recommendation, the Task Force TF 3 has proposed to add SP0 to help ensure that the design of hydrogen system and material selection 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 HAID 2, 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 the Section 5 “Lessons learnt”.