Statistics, lessons learnt and recommendations from analysis of HIAD 2.0 database

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Abstract

The Hydrogen Incidents and Accidents Database (HIAD 2.0) is an international open communication platform collecting systematic data on hydrogen-related undesired events (incidents or accidents). The database was initially developed by the Joint Research Centre of the European Commission (JRC) in the frame of HySafe, an EC co-funded Network of Excellence in the 6th Framework Programme. 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 (EHSP), an initiative started up in 2017 by FCH 2 JU, the EHSP has worked closely with JRC to improve the quality and accuracy of the information compiled in HIAD 2.0 by adding the information available through other international databases, incident/accidents reports and by uploading additional/new events to HIAD 2.0. Furthermore, EHSP periodically analyse the information in HIAD 2.0 to gather statistics, lessons learnt and recommendations through Task Force TF3. The first report summarising the findings of the analysis was published by FCH 2 JU in September 2019 [2] and a conference paper about HIAD 2.0 was presented at ICHS 2019 [3].

Subsequently, the EHSP and JRC have been continuously working together to enlarge HIAD 2.0 database with newly occurred events as well as adding high-quality historic events which were not previously uploaded to HIAD 2.0. This activity has facilitated the number of validated events in HIAD 2.0 to increase from 272 in 2018 to currently 566. JRC has also reviewed all previously input events to improve accuracy, traceability of sources and quality of the text. Furthermore, the overall quality of the published events has also been improved. Recently, EHSP has conducted statistical analysis to identify trends in the type of incident/accident, origin, causes, severity, etc; and analysed the lessons learnt and key recommendations that can be drawn from the newly added events which were consolidated before July 2020. This paper summarises the key developments and findings from the analysis.

1. Introduction

It is standard practice in the petrochemical industry to learn from past incidents and build experiences to improve design, operational procedures, devise mitigation measures to avoid the reoccurrence of similar events and improve the overall safety of the facilities.

Some of the established incident databases include the French ARIA [4] (Analysis, Research and Information on Accidents), the Major Accident Reporting System eMARS [5], the ~~U.S.~~U.S. Chemical Safety Board (*CSB*) [6], U.S National Transportation Safety Board

(NTSB) [7], U.S. Occupational Safety and Health Administration (OHSA) [8], etc. These are all general incidents databases covering different fuels, chemical, transportation and occupational safety and health. In the last two decades, with the global development of hydrogen technologies as one of the primary initiatives to combat global warming, at least two incident bases dedicated to hydrogen safety have emerged, i.e. the Hydrogen Incidents and Accidents Database (HIAD 2.0) [1] and H2LL within the Hydrogen Tools portal [9]. Brief descriptions are also given below for completeness while details can be found in [1,9].

HIAD 2.0 is a publicly available database collecting systemartic data and lessons learnt an international open communication platform collecting systematic data on hydrogen-related undesired events (incidents or accidents). The database was initially developed by the Joint Research Centre of the European Commission (JRC) in the frame of HySafe, an EC co-funded Network of Excellence in the 6th Framework Programme. It was updated by JRC as HIAD 2.0 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 (EHSP), an initiative started up in 2017 by FCH 2 JU, the EHSP has worked closely with JRC to improve the quality and accuracy of the information compiled in HIAD 2.0 by adding the information available through other international databases, incident/accidents reports and by uploading additional/new events to HIAD 2.0. The Hydrogen Tools Portal was developed by the Pacific Northwest National Laboratory developed through support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). The portal brings together and enhances the utility of a variety of tools and web-based content on the safety aspects of hydrogen and fuel cell technologies to help inform those tasked with designing, approving or using systems and facilities, as well as those responding to incidents [9]. H2LL is a database-driven tool within the portal to facilitate the sharing of lessons learned and other relevant information gained from actual experiences using and working with hydrogen. The database also serves as a voluntary reporting tool for capturing records of events involving either hydrogen or hydrogen-related technologies.

This paper summarises the continuous efforts of EHSP and JRC to enlarge HIAD 2.0 database and analyse the incidents to gather lessons learnt and formulate recommendations since the publication of the first report summarising the findings of the analysis by FCH 2 JU in September 2019 [2] and a conference paper about HIAD 2.0 at ICHS 2019 [3]. The joint efforts have resulted in the increase in the number of validated events in HIAD 2.0 as well as a new report summarising the statistics, lessons learnt and recommendations which will be published by FCH 2 JU ahead of ICHS 2021.

2. Enlargement and improvement of HIAD 2.0

JRC and the EHSP have continuously work together to add 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 currently 577. This number is also dynamic and continues to increase as new incidents are being continuously added by EHSP and validated by JRC. The quality of each entry has been assessed and its description improved whenever possible, striving, for example, for a full traceability to the sources and a harmonised classification of the causes. The sources of information include scientific literature, news items as well as the public but not hydrogen-specific databases mentioned in the previous Section: ARIA, eMARS, the US CSB, NTSB and OHSA. HIAD 2.0 contains also data based on reports of national nuclear authorities, and from databases not available anymore, such a the the UK IChemE [11], and the Japanese RISCAD [12]. For the newly occurred experts used their own professional networks to gather information and the JRC and EHSP hold discussions internally via emails and meetings before uploading the description to the database.

3. Overview of the incidents and the analysis procedure

Six members of the EHSP formed a working group under Task Force 3 (TF3). The template used previously to collect individual analysis of the allocated incidents was firstly modified to facilitate statistics analysis and distinguish recommendations from lessons learnt. The "European scale of industrial incidents" used in ARIA database [4] and the "Accidentology involving hydrogen" [13] are used to help to provide some quantification wherever possible on the amount of hydrogen involved, the human, social, environmental and economic consequences. The following procedure was followed by the EHSP members to perform the analysis:

- Six members of the EHSP firstly conducted individual analysis and then cross-checking the works in teams of two.
- The six members were divided into three teams of 2 each with responsibility for statistics, lessons learnt and recommendations.
- As the initial statistical analysis indicated the need to add additional columns in the analysis as well as to add these columns to the analysis underpinning the 2019 report, the experts have reviewed all the incidents again to address this.
- The consolidated spreadsheet from the experts were used to draw lessons learnt and the statistics, the preliminary report of both were then used to prepare recommendations.
- Throughout the process, where necessary, the experts also consulted the original descriptions in HIAD 2.0.

4. Statistics

As explained earlier, the number of incidents in HIAD 2.0 is dynamic as new incidents are being continuously added, validated and published. The analysis reported here is based on the 485 incidents 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 incidents were considered to be statistically relevant because it contains meaningful information. These incidents 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.

As shown in Figure 1, 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. Almost half of these incidents happened in Europe, while one third occurred in North America as shown in Figure 2. Asia accounts for about a sixth of the incidents, while other regions account for only 3 % of the incidents recorded. This is partial 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.

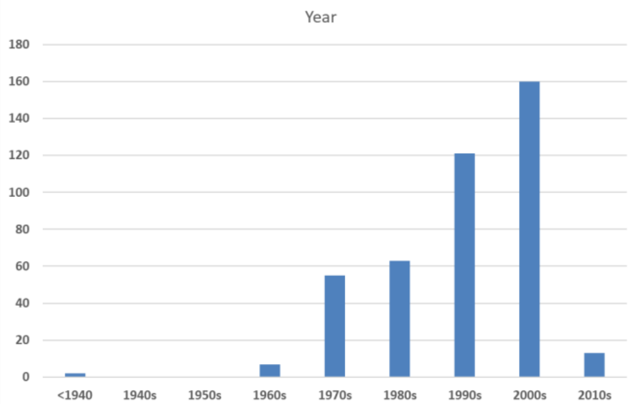

Figure 1: Distribution over time of the cases included in these statistics.

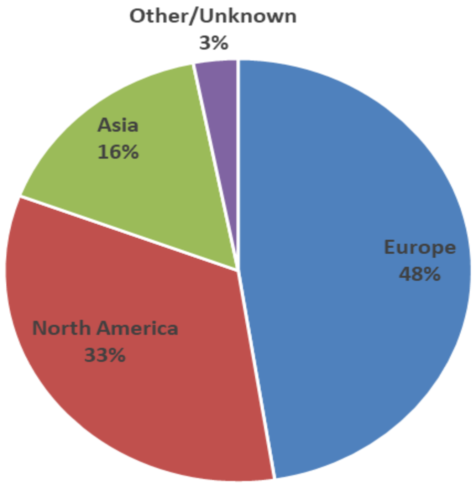

Figure 2: Regions of origin of the incidents considered.

It is widely known that hydrogen has a wide flammability range (4-76 %), requires little energy to ignite and reaches relatively high laminar flame speeds. Accidentally released hydrogen is prone to be ignited in the presence of an ignition source. Among the 426 incidents considered, apart from the 3 % near misses and 13 % un-ignited releases, hydrogen was ignited in 84% of the incidents with 56 % involved explosions and 28 % of the incidents resulted in only hydrogen fires . The 13 % incidents without ignition were attributed to a number of reasons, e.g. the unintended releases being promptly stopped. several incidents in this category just released relatively little hydrogen, etc. The 3 % near misses indicates that early detection and prompt action to mitigate any potential releases can still successfully avoid major hydrogen releases.

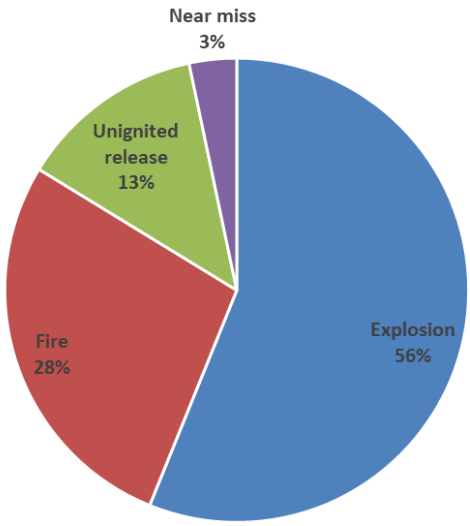

Figure 3: Consequences of the reported incidents.

Figure 4 present the analysis was also conducted about whether the incidents occurred during normal operation or outside. While the majority 70 % incidents occurred during normal operation, 27 % occurred outside normal operation i.e., during maintenance, special services or immediately after returning from maintenance to normal routine operation.

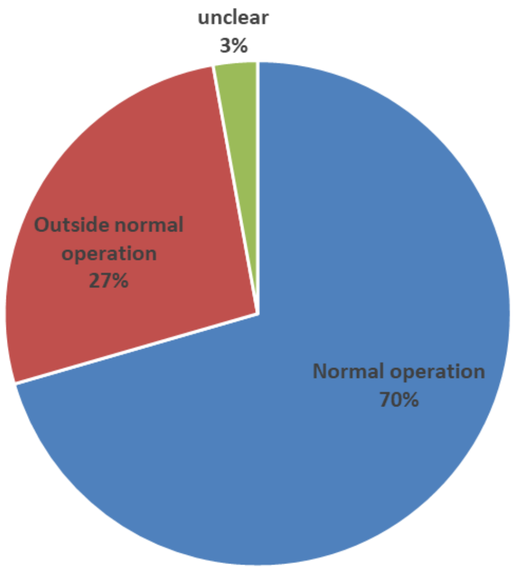

Figure 4: Operation mode when the incidents occurred.

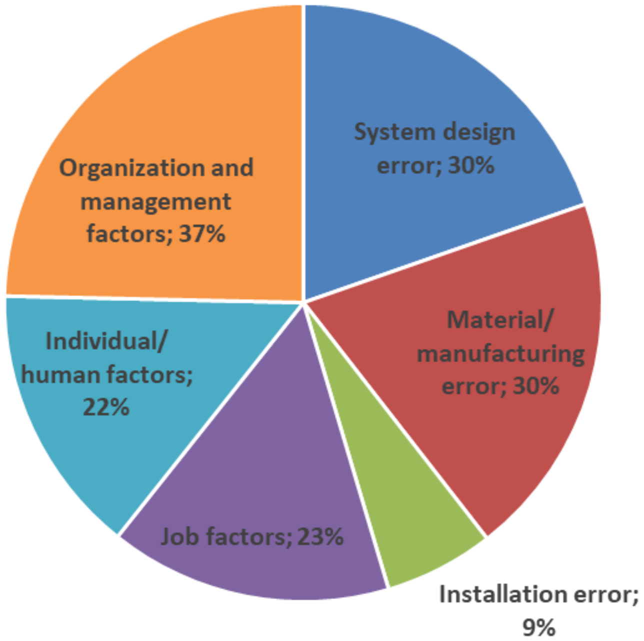

Figure 5: Causes of hydrogen incidents (multiple causes per event considered).

Figure 5 illustrates the statistics concerning the causes. As some incidents had multiple causes, the individual percentages here add up to more than 100 %. It is important to note that in 37 % of the incidents considered, organization and management factors were identified as at least one of the key responsible factors. System design errors and material/manufacturing errors have a share of 30 % each in the root causes. Job factors with 23 % as well as individual and human factors with 22 % play another significant role. Only 9 % of the incidents 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.

In 2019, the EHSP published a guidance document for “Safety Planning for Hyrogen and Fuel Cell Projects” [14], 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 1, 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.

The 426 incidents in HIAD 2.0 considered by the experts to be of statistical value as of July 2020 were individually analysed by six safety experts based on the available incident information. The recommendations were provided against each incident based on Safety Principles (SP1-SP10). However, it is 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 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 the poor design of the hydrogen system or use of material which is not compatible with hydrogen. It is hence proposed to add a new safety principle SP11 to account for poor design of hydrogen system and/or material selection. While this proposition has yet to be adapted by the Task Force 1 of the EHSP, it is included in the current analysis for clarity.

Table 1 The Safety Principles [14]

Number	Safety Principle	Explosion Protection Tier
SP1	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 results of the analysis are shown in Figure 6. Out of the 426 incidents considered, the major contributing factors were from SP9 (23 %), SP10 (14 %) and SP11 (11 %). 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 to these incidents. Finally, 11 % of the incidents show that the poor design of the hydrogen system and the use of incompatible material being the root cause.

As a next step, it is further checked to see whether statistics on SP follow any trends with respect to the year of the incident. Figure 7 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 the personnel and incident reporting system.

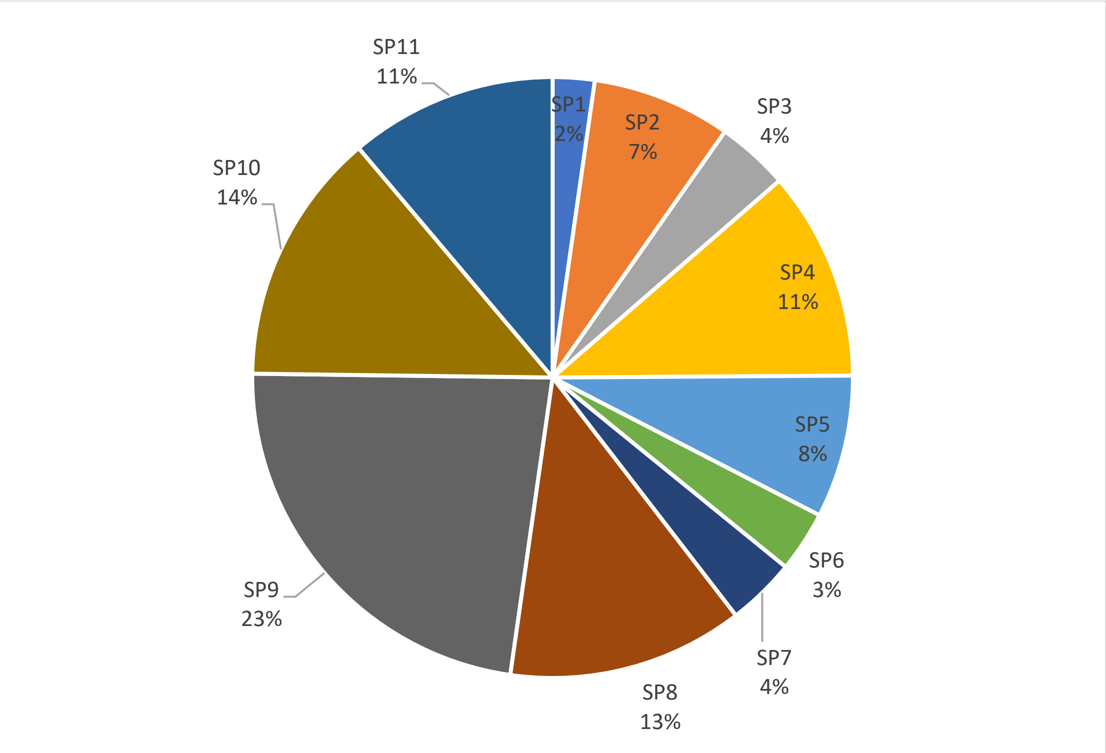

Figure 6: Statistics showing the number of incidents reported with different Safety Principles (SP).

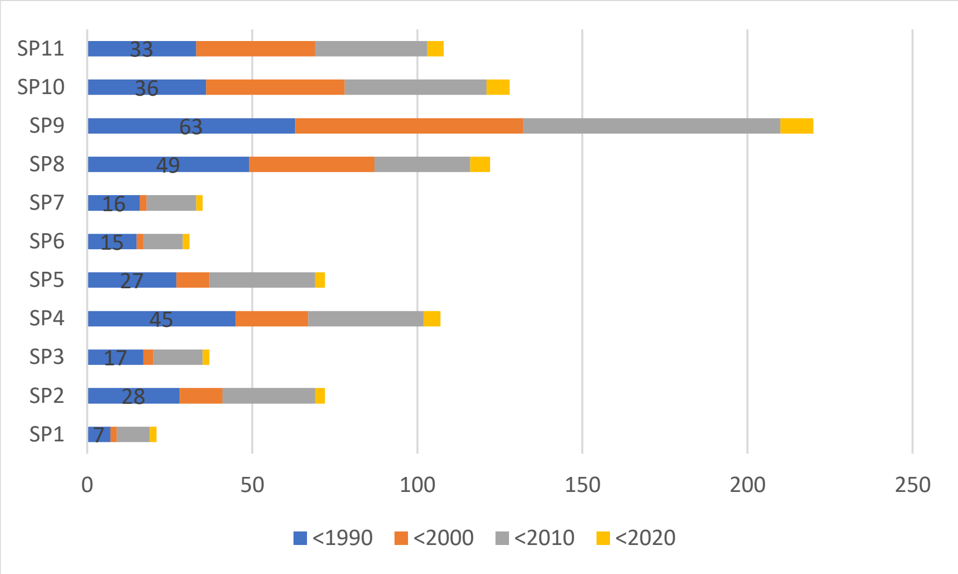

Figure 7: Variation of recommended SP with reported year of incident.

5. Lessons learnt

This section is devoted to experiences distilled from the incidents added to HIAD 2.0 databases since the release of our previous report in 2019. Despite the lessons learnt from each specific event are quite specific and particular to the event conditions itself, this section aims to provide some insights about some common aspects detected in the lessons learnt compiled in the experts' individual reports. To facilitate the reading, the lessons learnt are grouped into several sub-sections according to their causes. Six categories have been defined, three of which relate to the system itself in terms of its definition, manufacture and installation. The last three are related to operator errors, which are further classified into three sub-categories: job factors, individual/human factors and organisation and management factors.

An overarching lesson is that some incidents might consist of several causal events that, if occurred separately, might have little consequences; but if these minor incidents occurred simultaneously, they could result in extremely serious consequences. Some incidents were caused by multiple reasons while some involve cascading effects. Although some key information relevant to the description of lessons learnt was extracted in the paper, the readers are recommended to consult the original event description in HIAD 2.0, where there are more details for specific incidents of interest.

5.1 Lessons learnt related to system design

Some design issues were identified being 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, which were included in the description.

Corrosion related: Considerable amount of incidents were found to be related to corrosion, the occurrence of whichwas not detected through regular inspection, prevented from maintenance, or lack of due consideration of the hydrogen compatibility of materials used. For example, incident ID95 was caused by the corrosion of the heat exchanger. Other incidents caused by corrosion include incidents IDs: 83, 104, 122, 131, 179, 194, 196, 208, 210, 246, 261, 478, 546, 567, 568, 615, 616, 648, 707.

Design related: 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, incident ID734 was partially caused by lack of clear separation of combustible gas from the oxidizer and ignition source; incident 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. incident 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 a 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.

Venting: Some incidents were caused by the lack of provision for safe venting of hydrogen and some were attributed 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, incident 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; incident ID674 was suspected to be due to the ventilation system has not been activated; and in incident ID680, the cylinders were stored indoor without adequate ventilation and detections system. It is suggested to safely site the vents such that the hydrogen plume does not reach the ignition source.

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

Extreme weather conditions: Icing could result in blockage and cause over-pressurization in some systems. In incident ID552, the blockage resulted in the fracture of the second stage cylinder of a hydrogen compressor. Heavy rains could lead to water accumulation, e.g. the explosion incident 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 the 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. incident ID572.

Second-order redundancy on critical systems: Provision of second-order redundancy in some hydrogen facility could have prevented some incidents, e.g. for incident ID553 which involved incorrectly calibrated transmitters, secondary stops fitted to key controllers/valves could have limited the gas flows due to malfunction (ID553). In this incident, the investigation of the incident was hampered by the loss of the relevant instrument record charts.

Pressure relief valves: Some incidents indicated inadequate design and/or installation of pressure relief valves in some pressure systems, e.g. incident ID808. Incident ID562 was also 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.

Hydrogen accumulation in confined/semi-confined spaces: Several lessons can be learnt in relation to this: (1) Explosive mixture with hydrogen in the stagnant zone of pipe systems could result in incidents such as those in incidents ID533 and ID571 concerning radiolytic gases in nuclear power plants; (2) Internal pump might create a vacuum inside tanks with possible air ingress to form an explosive atmosphere, e.g. incident ID551; (3) 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 ID568; and (4) Pipe trench with hydrogen pipes near other hot pipes is a potential hazard, e.g. in incident ID544 and requires clear separation with due consideration for specific firefighting.

Hydrogen generation due to malfunction: ID522 hydrogen explosion in the core spray system of a nuclear power plant was traced back to the design which was vulnerable to hydrogen generation due to water splitting by the neutron radiation from the reactor core. Event ID492 in a nuclear power plant was due to the formation of hydrogen by radiolysis of reactor water in a core, which exploded and possibly transited to the 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. ID525 was also caused by accidentally generated hydrogen. Event ID514 was linked to a ruptured seal on a valve in the blast furnace gas pipework that caused the release.

Equipment factor: The explosion and fire in incident ID 609 were due to reverse flow in the raw material tank caused by the excessive opening of the valve, which was suspected to be related to maintenance issues or inappropriate materials. Equipment factor and poor apparatus were also mentioned in incident 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 incident ID613.

Miscellaneous: An important lesson is to ensure inherently safe design. Some incident was caused by a design problem. For example, the explosion in 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 were not identified, the operator has to implement plant modifications to prevent recurrences of similar incidents.

5.2 Lessons learnt related to system manufacturing/installation/modification

System manufacturing issues were identified being 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: Incident 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. Incident ID615 involving vapour cloud explosion was traced back to the crack in a storage tank releasing gaseous hydrogen to the atmosphere. The likely cause was the use of materials not compatible with hydrogen and the lack of periodic audit and maintenance to detect the defect promptly.

Venting system: Hydrogen venting system malfunctioning could lead to severe consequences, e.g. in ID536, a 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.

Weak points: Some weak points resulted in numerous incidents. Examples include gauge glass for liquid tank level monitoring, flange connections, welded junctions, etc.

5.3 Lessons learnt related to operator errors

Everyone can make mistakes 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 3, human errors, as well as technical errors, were quite often the cause of incidents.

In the following, for lessons learned from past incidents, the classification [15] proposed by the Health and Safety Executive (HSE) is adapted, which identifies the factors that make operator errors more or less likely to occur. The three categories that influence human performance are the job itself, the individual and the organisation. The definition of each of these categories can vary in different situations and by different authors. The following lists some examples to help to illustrate 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. Several incidents showed poor or not updated operative and maintenance guidelines/instructions. Moreover, very typical is the presence of external contractors for maintenance or additional installations, clearly showing the incapability of the organisation to communicate beyond its own boundaries.

The statistics gathered from HIAD 2.0 as described in Section 3 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 category were initially caused by a 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 were caused because maintenance and inspection were not carried out regularly and in timely. Event ID 185, for example, was caused by poor maintenance resulted in material failure. Faulty maintenance was also found to result in a 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 event was also 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 IDs 194, 196 and 621 and bolt failure in event ID405 could perhaps also have been avoided by regular inspections of these components, similarly, event IDs 101, 702, 703, 708 were also due to the lack of regular inspection.

Special attention for safety devices during maintenance: Fittings, gaskets, flanges, valves, etc. are often identified as weak points of hydrogen systems. Some incidents were caused by a 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 IDs 156 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 a hydrogen leak from the damaged valve. Similar incidents of IDs 249 and 601 involved faulty non-return valves. Incidents IDs 542, 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 ID 678, which was caused by the negligence of the regular inspection of the gasket retainer and lock ring and their appropriate maintenance.

Individual/human factors*:* In event ID 679, the pipe was incorrectly installed, which 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.

Lack of clear instructions: Some incidents were caused by a 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 is not a special ATEX type was also thought to be partially responsible. Another example was event ID 672, where incompetence in developing and following procedures led to an explosion and nuclear waste release to the atmosphere and water.

Accidentally generated hydrogen: In several incidents, the flammable gas was not initially present but was produced during a chemical reaction without detection and ventilation. This mainly concerns reactions between acids and metals (event IDs 49, 192, 234 and 321) or unexpected chemical reactions (event ID 123). Wrong identification of chemical components was found to accidentally produce a strong explosion in event ID 530.

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. The lack of proper checking to confirm that it was safe to resume operation in the section of the plant could have prevented this incident.

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

5.3.2 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:

- 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 on 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 ID 719.
- Some incidents were caused because the pressure of the filter was not monitored, e.g. event ID 661.
- The system was not purged regularly, e.g. event ID 661 or with sufficient nitrogen, e.g. event ID 663.
- The design and operation conditions were not adequately verified, e.g. event ID 664.
- Emergency procedures were not followed and updated, e.g. event ID 665. Another example was event ID 666, in which because the start-up procedure was not correctly followed, a 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 ID 681 was caused by a lack of purging of the accidentally generated hydrogen. Event ID 688 was caused by hydrogen escaping when a venting valve was opened for inspection of a cap and a similar event also occurred 5 years ago, indicating a consistent lack of adequate staff training and inspection procedure. Some very good practical lessons can also be gathered from ID 685 concerning the consequences of not providing appropriate training for operating staff for is cracker compressor.
- Some incidents, e.g. IDs 495 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 ID 701 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. ID 429.

- Event ID 614 was also traced back to the human factor, unsuitable action/operation and operation mistake/work mistake.

5.3.3 Lessons learnt related to organization and management factors

Management and organization factors are also 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 a grinding machine or impact wrench (ID 631). Regarding welding, Case ID 496 was caused by welding. Following the incident, the plant operator imposed additional controls on welding activity, consisting in he analysis atmosphere samples, in the case systems had contained flammable gasses and analysed before initiating an arc to determine if explosive gasses were present.
- Some incidents could have been preventing by procedures for fast isolation of the release sources.
- Some incidents were traced back to a lack of clear guidance about the lifetime of critical components in addition to their regular inspection and replacement.
- Event ID 546 was due to a lack of explosivity control before maintenance on a running plant.
- Event ID563 was due to a lack of clear distinction between emergency and operating alarms in hydrogen system units.

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 means to prevent incidents through inherently safer design.

In formulating the recommendations, links are made to the relevant safety principles [14] wherever possible.

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 4, 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 ones 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 a 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 thorough 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

<u>Hydrogen energy applications</u>

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 safe considerations. This section is focused on specific hydrogen applications of interest for the FCH community that have been selected. Note that these are the high-level preliminary recommendations given by the sector of the highest interest of FCH JU applications. These recommendations will be improved in future investigations.

<u>Hydrogen transport and distribution</u>

Among the 485 incidents considered, 39 incidents were linked with hydrogen transport and distribution representing 10 un-ignited hydrogen releases and one release of liquid hydrogen (ID262), 12 explosions and 13 fires, only 4 near-misses were found (IDs23, ID144, ID171).

The general recommendations applied to almost all incidents is that effective 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 (see an example of ID519, where the second accident led to an explosion and one injured person).

<u>Recommendations to reduce traffic incidents</u>

Traffic incidents including rollover and crashing with other vehicles were the cause of almost all near-misses, three incidents with un-ignited hydrogen release (IDs100, 109 and 337) and two fire incidents (IDs336 and 586). 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 [16].
- Driver should be trained for emergency response and fire-fighting

The cause of several other incidents was related to operational fault including faulty connections on liquid hydrogen venting system (ID43), improper handling of liquid hydrogen transfer (ID57), rupture of connecting pipe during loading of bottles rack (ID179), hydrogen gas leakage from a cylinders fall during the transportation (ID338, ID596), inappropriate hydrogen transfer (ID590), inappropriate maintenance (ID475) or installation error (ID541). The recommendations gathered from the lessons learnt from 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 (e.g., 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 (ID385, ID384 ID534) or poor welding (ID567), unexpected chemical reactions (ID27) and unsafe design (ID17). The following recommendations are made in consideration of these:

- Perform Process Hazard Analysis for the new/updated installations (SP1-10);
- Use materials that 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 (SP11); and
- Install high fidelity leak detection and other extra mitigation barriers (e.g., SP4, SP8).

Recommendations related to material failure

The failure of fittings, valves, tanks (ID42, ID58, ID156, ID262), venting system (ID536) and even pipeline due to corrosion (ID478) can lead to fire and explosions. Even safety measures such as rupture disks (ID382) and venting systems (ID536) if not properly integrated in the overall safety design, can cause unwanted consequences. The following general recommendations can be given in relation to preventing such failure:

- Regular check and maintenance and inspections should be carried out (ID42, ID262, ID382, ID478, ID487); (SP10)
- The operator should consider the installation mitigation barriers such as hydrogen sensors (ID42, ID270), pressure sensors (ID58, ID156), 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 (ID42, ID139) (SP3, SP5); and
- Control the proper functioning of hydrogen venting devices (ID536).

6.2 Hydrogen-powered vehicle

Special interest in hydrogen safety represents incidents occurred with hydrogen-powered vehicle. Nowadays, there is only one declared incident in HIAD 2.0 - ID82 (Postal Service mail truck trailer). This event does not correspond to an accident, it represents a near-miss corresponding to a traffic accident including an experimental hydrogen-powered vehicle. This near-miss demonstrates that both safety principles were followed. Recommendations are mainly dedicated to organization safety principles:

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

6.3 Laboratory / R&D

Attention must be paid to R&D installations and laboratories involving hydrogen. Among the incidents considered, thirteen were reported by the 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 three categories:

- Perform an exhaustive risk analysis for each specific activity to identify safety measures required, including leak detection. Inadequate risk assessment has led to incidents such as explosion (ID314, ID429, ID510, ID646, ID697) (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 severe consequences involving explosion (ID28, ID47, ID380, ID314, ID429, ID497) (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 (ID249), electrolyzer (ID477), Cylinder (ID525) (SP8)

6.4 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 into two categories:

- Perform periodic and frequent surveillance and maintenance of equipment. Material failure and malfunctioning of systems can lead to hydrogen leak and explosion as in incidents ID35, ID164, ID182, ID250.
- Continuous updating of testing procedures, including ATEX requirements, especially in case of changes (management of change approach). Incidents involving serious fire and explosion occurred due to a deficient hazard assessment and deficient testing protocol (ID 152, ID561, ID562, ID680) SP1-10.

7. Concluding remarks

The continuous joint efforts of the EHSP and JRC have facilitated the number of validated events in HIAD 2.0 to increase from 272 in 2018 to currently 566. JRC has also reviewed all previously input events to improve accuracy, traceability of sources and quality of the text. Furthermore, the overall quality of the published events has also been improved. Recently, EHSP has also conducted statistical analysis to identify trends in the type of incident/accident, origin, causes, severity, etc; and analysed the lessons learnt and key recommendations that can be drawn from the newly added events which were consolidated before July 2020. This paper summarises the key developments and findings from the analysis while a detailed report will be published by FCH 2 JU before ICHS 2021.

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