Summer Capstone Project Report

P^2SAC Project

Determination of Common Root Causes of 300+ Global Incidents

Deep Patel

Mentor: Dr. Ray Mentzer

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ABSTRACT

Process safety incidents throughout history have caused the loss of human life and damage to the environment. It is necessary to learn from history and adapt accordingly. This study consisted of 331 global incidents, categorized into 14 different industry types: chemical, aerospace, oil and gas, refining, etc. The incidents were taken from three databases and each incident was reviewed thoroughly. Efforts were made to analyze each incident's details, including the region and year of occurrence, fatalities, public impact, economic damage, and, most importantly, the two most impactful root causes. Most of the incidents listed in the analysis resulted in more than $1 million in damages, while several incidents caused more than $1 billion in damages. If the cost is adjusted to the present-day value, then the number of incidents crossing the one billion mark increases dramatically. It was observed that around 68% of the incidents had a public impact in the form of offsite fatalities, damage to nearby buildings, and/or community impact in the form of evacuation, curfew, clean-up tasks, etc. Chemical industries had the most fatalities in both Database 1 and 2, which included 156 global incidents investigated by students of Purdue University, and 101 incidents investigated by the Chemical Safety Board respectively. However, in Database 3, which included 74 incidents listed in Marsh's latest report on '100 Largest Losses in Hydrocarbon Industry 1974-2023', the upstream sector incidents had the highest number of deaths [5]. A trend was noticed in the analysis of the root causes of 331 incidents with safety culture, operating procedures, process hazard assessment, and mechanical integrity being the most common root causes from the list of eighteen contributing factors as provided by the Occupational Safety and Health Administration (OSHA) and Center for Chemical Process Safety (CCPS) [8, 9]. This study also showed the relation of root causes with the type of industries. These findings can be utilized by industry stakeholders to improve their process safety performance.

INTRODUCTION

Process safety has become an integral part of any processing facility today. It is a disciplined framework that maintains the integrity of operating systems and processes handling hazardous substances. An event that involves disruption of such systems and release of either dangerous substances or energy, which causes damage to personnel, environment, or property or has the potential, is termed a process safety incident. Hence, mitigating such incidents and ensuring a safe working environment is a prerequisite. Process safety incidents, often mistakenly identified as from a few industries, occur across a wide range of sectors, leading to significant harm to life, property, and the environment. These incidents differ from occupational safety incidents, examples include slips, falls, trips, etc, which, though more frequent, tend to be less severe.

A significant challenge in this field is the absence of a comprehensive, global, multi-industry database of process safety incidents. Such a database would aid organizations in enhancing their safety management systems and identifying the root causes of incidents. Despite several attempts to create incident databases, factors such as regional constraints and restricted reporting affect their accuracy.

One study analyzed 81 process safety incidents across 14 industries, including chemical, food, pharmaceuticals, and fireworks. The analysis identified safety culture, emergency response, and mechanical integrity as common root causes [1]. Personnel training, operating procedures (OP), management of change (MOC), and process hazard assessment (PHA) were also found to be prominent contributing factors [1].

A similar study of 73 global process safety incidents within the pharmaceutical industry highlighted hazard awareness and identification, operating procedures (OP), design, safety culture (SC), preventive maintenance (PM), and safeguards as key root causes [2]. Another study from 2021, analyzed 79 incidents from 2010-2019 in the US Chemical Industry and found design, PM, and safeguards as the top three contributing factors [3].

While the three studies cited above were done in conjunction with the Purdue Process Safety & Assurance Center several others have been done, including a study on 68 incidents investigated by the Chemical Safety Board (CSB) which found preventive maintenance, operating procedures, design, and emergency response (ER) as some of the most common root causes [4]. It was also seen that as the age of facilities increases, the probability of incidents also increases due to outdated technology, standards, and practices, eventually leading to inadequate PHAs. Thus, one concludes that process safety management activities should be dynamic, and learnings from past incidents should be considered. Hence, as per previous studies, certain root causes like OP, PM, design, etc seem to be the most prevalent.

Marsh's 28th edition of '100 Largest Losses in the Hydrocarbon Industry, 1974-2023' included two recent incidents [5]. This list showed that 35% of incidents were in the refining industry, and 32% in the upstream sector. Effective emergency response, communication among personnel, and regulatory compliance were crucial in mitigating incidents and minimizing damage. The average economic loss per incident was $529.7 million, adjusted for present-day values, with upstream incidents contributing the most.

This study aims to analyze over 300 process safety incidents, examining their root causes, industry types, number of fatalities, and economic and public impact. The analysis includes findings from Purdue University's student reports [7], CSB investigation reports, and the Marsh report. Analysis of this database will be valuable for industry stakeholders to improve their process safety performance.

INCIDENT DATABASE

The incidents included in this study came from a variety of sources, the student reports of Dr. Ray Mentzer's ChE 420/597 class, CSB investigation reports, and Marsh's 28th edition of '100 Largest Losses in the Hydrocarbon Industry, 1974-2023'. The class reports result from student team investigations of incidents, typically 15 – 20 pages; around 55 reports a year over the past eight years, with independent analyses of many incidents across years. Various news reports and articles from BBC, Reuters, etc were also considered for incidents that occurred in North America, Europe, and Oceania (Australia and New Zealand). For developing nations, an attempt was made to get information related to the incidents from government bodies or similar media outlets that are more prevalent. Information regarding the type of operation, number of fatalities, and economic and public impact has been provided in this study.

This study consists of three different databases from the above sources and attempts have been made to conduct consistent analyses of all the datasets. As stated earlier, the study includes: (1) 156 global incidents from the student reports [7], (2) 101 incidents that occurred in the US, reported by the CSB [6], and (3) 74 global incidents listed in the most recent Marsh report [5]. The root cause analysis for the incidents reported by the CSB was comparatively less complicated than others, as a comprehensive analysis is readily available. However, due to a variety of reasons, detailed investigation reports of incidents that occurred in developing countries are frequently not available, though this study has incorporated findings from various sources and a best effort has been made to determine the mentioned factors for the analysis.

Process safety incidents result from several shortcomings like weak process safety management systems, inadequate design, lack of skilled personnel, human negligence, etc.

This study attempts to find the most common factors that led to such incidents, so they can be addressed, and suitable measures can be taken to mitigate the hazards. The CSB investigations provide a detailed description of the root causes, while this study aims to categorize the root causes into 14 different types, which are listed by the Occupational Safety and Health Administration (OSHA) [8]. These root causes are the most commonly identified factors leading to safety incidents, for example, mechanical integrity, process hazard analysis, design, and so on. Safety culture, as one of the root causes was seen in most of the incidents but it was a more predominant factor in developing nations. Similarly, lack of regulations and oversight was also a major contributing factor in such countries. The 14 most common root causes as identified by OSHA are listed below:

1. Safety culture (SC)
2. Process hazard analysis (PHA)
3. Mechanical integrity (MI)
4. Emergency preparedness and response
5. Personnel training (PT)
6. Operating procedures (OP)
7. Preventive maintenance (PM)
8. Management of change (MOC)
9. Work permit system
10. Regulations and regulatory oversight (Regs)
11. Design
12. Human factors (HF)
13. Hazard awareness and identification
14. Facility siting

Table 1, provided in the Appendix, consists of a detailed list of these factors along with their definitions as provided by OSHA Process Safety Management [8] and the Center for Chemical Process Safety's (CCPS) four pillars of process safety and 20 elements [9].

The database is divided into three parts to gain more insights into the relationship between the incident, region, type of operation, fatalities, and economic and public impact.

Database 1:

It consists of the 156 incidents covered in student reports from Purdue University [7]. These incidents have been categorized under 14 different types based on their respective industries. These industries are listed as follows:

1. Agriculture
2. Chemical
3. Fertilizer
4. Manufacturing
5. Mining
6. Oil and Gas/Upstream
7. Pipeline
8. Storage
9. Food
10. Aerospace
11. Powerplant (Nuclear/non-nuclear)
12. Refinery
13. Shipping/Boat
14. Other

In this list, the ‘Other’ category represents the incidents that occurred in electroplating, water treatment/ waste disposal, military, utility, fuelling station, water supply (dam), and entertainment sectors. Attempts have been made to gain accurate information regarding the monetary damage of the global incidents, however, due to several socioeconomic factors, we were not able to gather information on all incidents.

Database 2:

It consists of 101 incidents that have been investigated by the CSB, and as all of them occurred in the US, the number of industries across which they occurred is less than the previous database:

1. Chemical
2. Manufacturing
3. Oil and Gas/Upstream
4. Storage
5. Food
6. Refinery
7. Other

This list’s ‘Other’ category consists of incidents in the waste treatment and renewable energy sectors. The ‘Manufacturing’ sector in Databases 1 and 2 includes a variety of industries that are involved in the production of fireworks, ammunition, pharmaceuticals, polymers, explosives, and paper.

Database 3:

It comprises 74 incidents from the Marsh report, with the remaining 26 incidents removed from the original report as those were already covered in the previous databases [5]. In this, the industries were classified into 5 types, namely:

1. Upstream
2. Refining
3. Gas Processing
4. Petrochemicals
5. Terminals/Distribution

In summary, Database 1 includes global incidents over a broad time horizon and industries, noting that the analyses have been done by senior undergraduate & graduate students. Database 2 incidents analyzed by CSB have the most thorough analysis but are all US incidents since 1998 and primarily chemical plant and refinery related. Database 3 incidents have been thoroughly studied by Marsh, global, yet only include the hydrocarbon industry. To maintain consistency, no monetary damage numbers have been changed to reflect current values in any of the databases. Note that such information is often not available, and when available it is often not clear if it reflects an estimate of damage, actual repair costs, and whether lost production is considered.

ANALYSIS

A total of 331 incidents were reviewed in this analysis. Out of these 49.4% of incidents occurred in the US, while a noticeable number of incidents occurred in Asia, Europe, South America, and Oceania. Figure 1 shows the distribution of incidents according to the country or region of occurrence for Database 1. The 'Other' category in Figure 1 consists of countries like Venezuela, Switzerland, Thailand, Kuwait, Brazil, Algeria, Norway, Turkey, South Korea, Lebanon, and Indonesia. Database 3 consisted of more than two-thirds of the incidents occurring in North America and Europe.

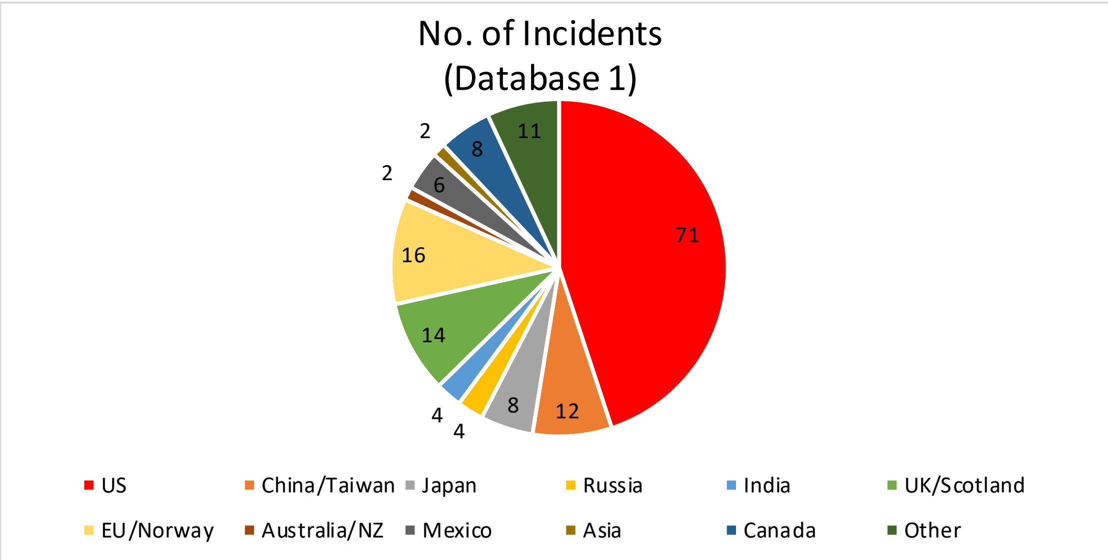

Figure 1: Incident distribution based on their occurrence region from Database 1.

In this analysis, the distribution based on operation type for Database 1 was notably broader than that of the other two databases, which can be seen in Figure 2.

It was seen that the number of process safety incidents in chemical facilities dominated at 56.7% of the total incidents in the CSB database followed by refineries (~23%). In comparison, around 39.2 % of incidents listed in Database 3 occurred in the upstream sector, followed by refineries (32.4%). Refinery and chemical plant incidents were frequent in all three databases.

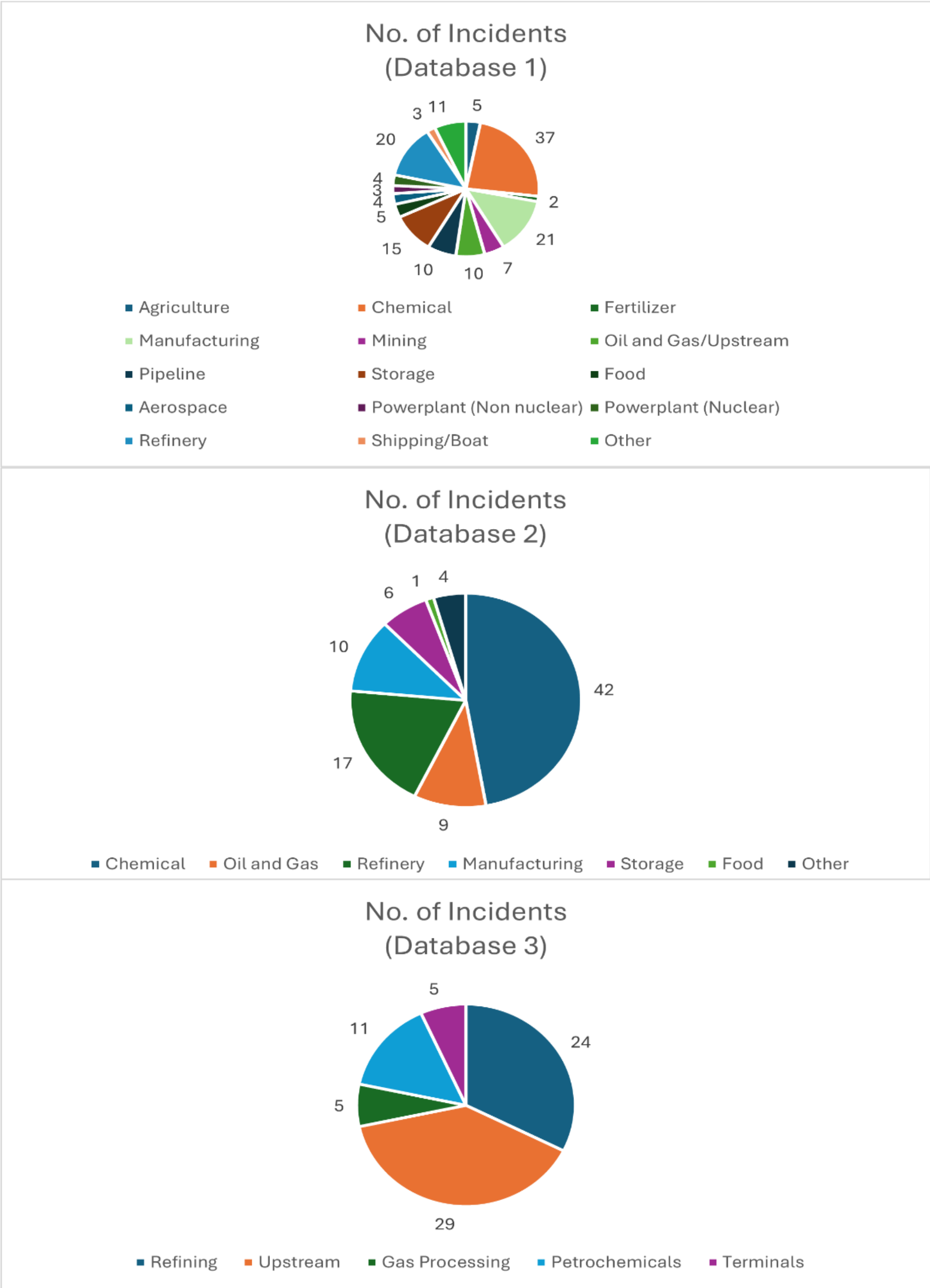

Figure 2: Distribution of incidents based on type of operation from Databases 1,2, and 3

Public Impact is defined as impact on humans and/or property beyond the physical boundaries of the facility. In this analysis, it was noted that a large proportion of incidents listed in Database 1 had a public impact (78.3%), as seen in Figure 3. Similarly, in Database 2, 59.4% of incidents had a public impact. However, in Database 3, it was seen that 41.9% of the incidents had a public impact. The reason for this difference is the type of operation of the majority of incidents listed in the Marsh Report [5]. As a large chunk of incidents occurred in the upstream sector, there was no noticeable impact outside the site boundaries. In offshore oil and gas incidents, there are typically only site personnel nearby, although there could be oil spill impacts.

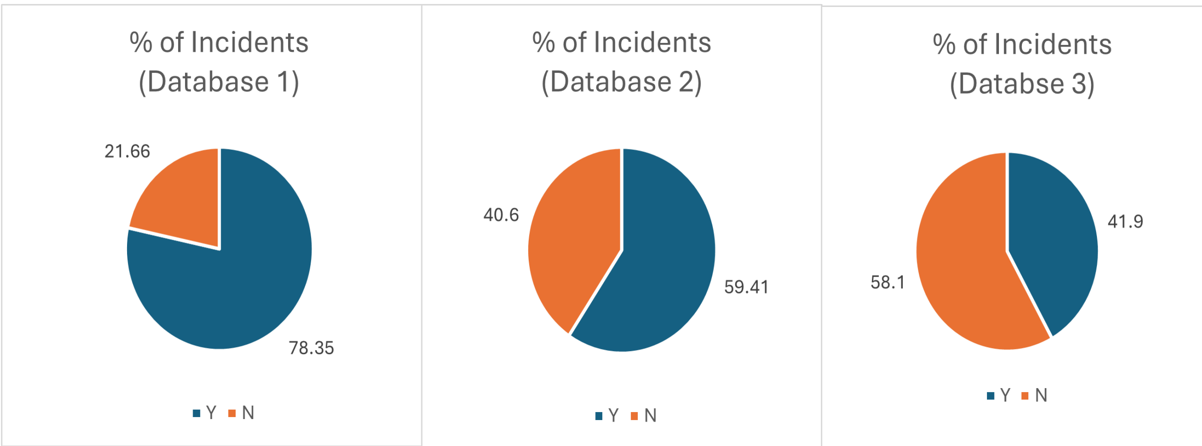

Figure 3: Number of incidents that had a public impact in Databases 1,2 and 3.

Abbreviations: Y: Yes, N: No

Figure 4 provides insights into the number of fatalities and incidents along with the timeline of the incidents listed in Database 1. It can be noticed that the frequency of incidents increased with time, however, the number of fatalities per incident decreased. A similar trend was seen in the other two databases as well, with the frequency of incidents increasing from the early 1990's. It was worth noting that 57 process safety incidents took place between 2006 and 2010, with 30 occurring in the US itself. Undoubtedly incident reporting has improved with time, while those with significant impact would likely be noted globally.

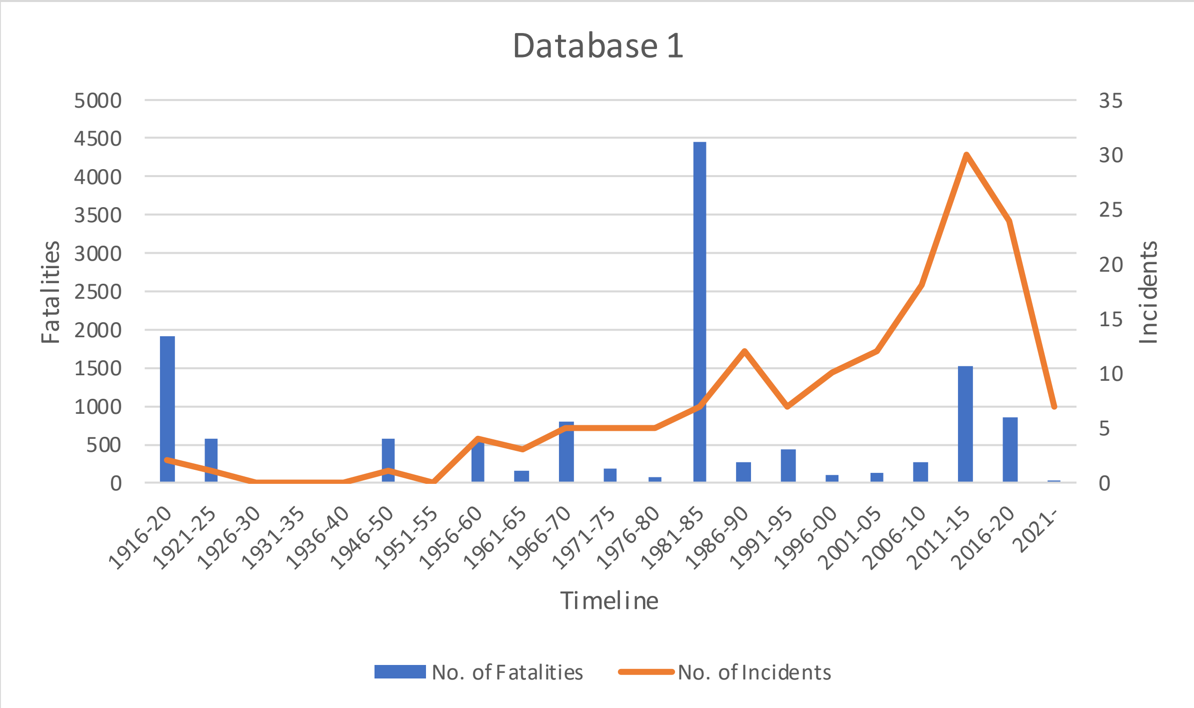

Figure 4: Relation between the number of fatalities and incidents over the years from Database 1.

Process safety incidents often result in injuries to personnel and, in some cases, deaths. This analysis also consists of the number of fatalities for each incident listed. An effort was made to find accurate numbers, however, in certain incidents, the death count was difficult to estimate due to the long-term effects of those incidents. For example, the Minamata mercury release incident in Japan, which occurred over multiple decades (1951-2011), resulted in the loss of more than 900 lives due to the consumption of contaminated fish and shellfish over the years. Similarly, the infamous Chernobyl nuclear disaster of 1986 resulted in thousands of fatalities due to the long-term effects of radioactive exposure. Hence, this analysis considers the number of short-term fatalities which were the direct result of the incident.

Chemical industries are prone to process safety incidents and this analysis showed that these industries have had the highest fatalities, evident from Figure 5. A similar analogy was seen in Database 2 as well. However, as Database 3 consists of incidents from the Marsh Report which mainly focuses on hydrocarbon industries, the upstream sector had the highest fatalities, followed by the terminals sector (downstream).

Figure 5: Relation of No. of Fatalities with Type of Operation (Database 1, 2 and 3)

The fatalities in the petrochemicals and gas processing sectors decrease with time. Figures 6 and 7 show the trend followed in these sectors. These relations are based on the incidents listed in the Marsh Report [5].

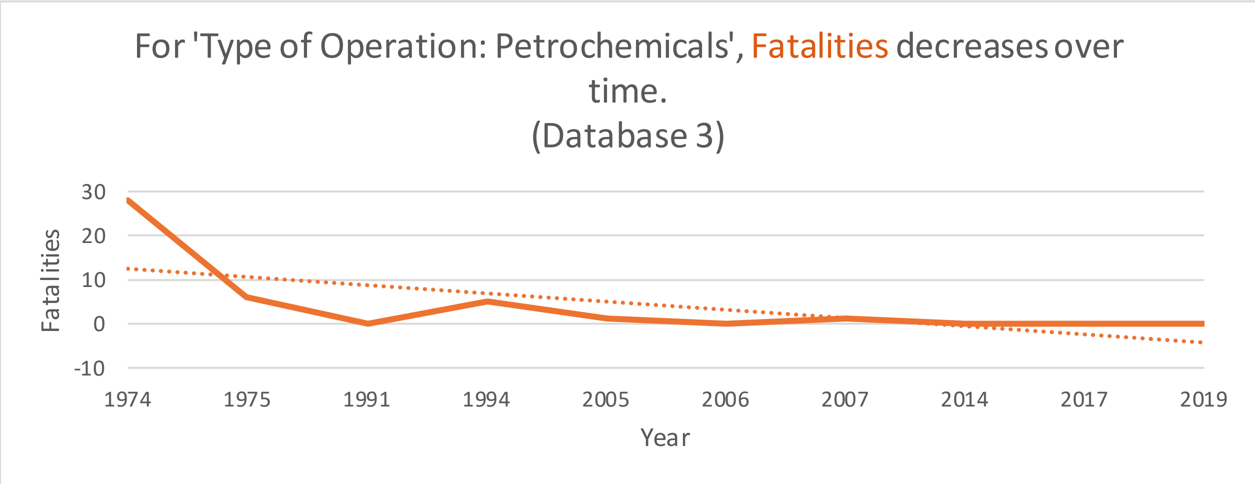

Figure 6: Relation between fatalities and time in the petrochemicals sector (Database 3)

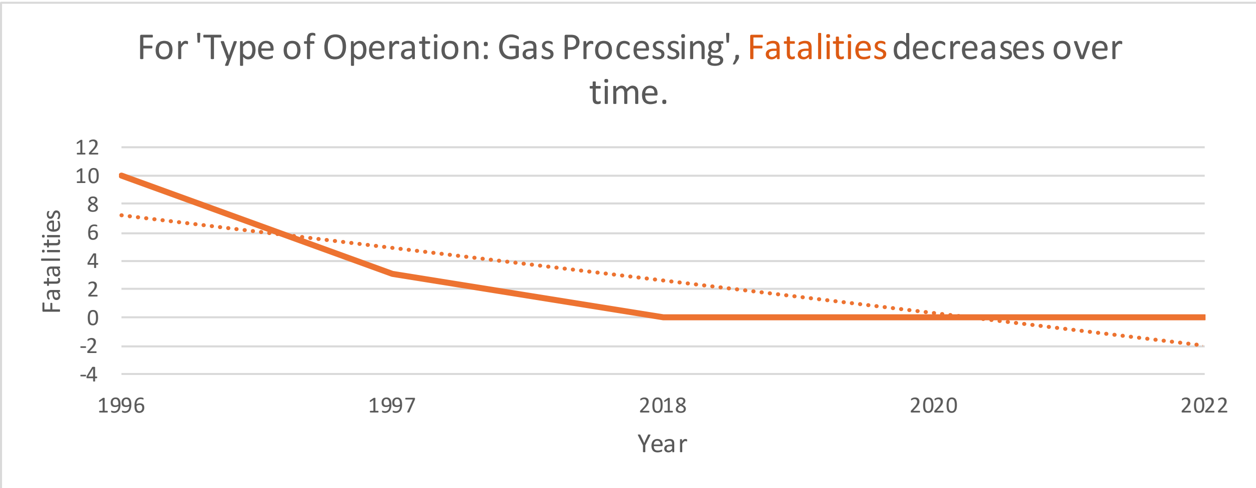

Figure 7: Relation between fatalities and time in the gas processing sector (Database 3).

A similar trend was seen in the manufacturing and shipping sectors according to the incidents listed in Database 1. It was also interesting to note that the incidents listed in Database 1 which occurred before the 2000's, again saw chemical industries leading with the greatest number of incidents as well as fatalities, while refineries followed in terms of the number of incidents. The shipping sector saw the second-most fatalities, however, the number of incidents in this sector was on the lower side. Figure 8 shows the trend between the number of incidents and fatalities along with the type of operation. The reason for this trend in the chemical sector is due to the infamous Bhopal gas tragedy of 1984, which claimed the lives of almost 4000 people, whereas the shipping industry saw a disastrous event in 1917 known as the Halifax explosion, which resulted in the loss of 1900 lives [7].

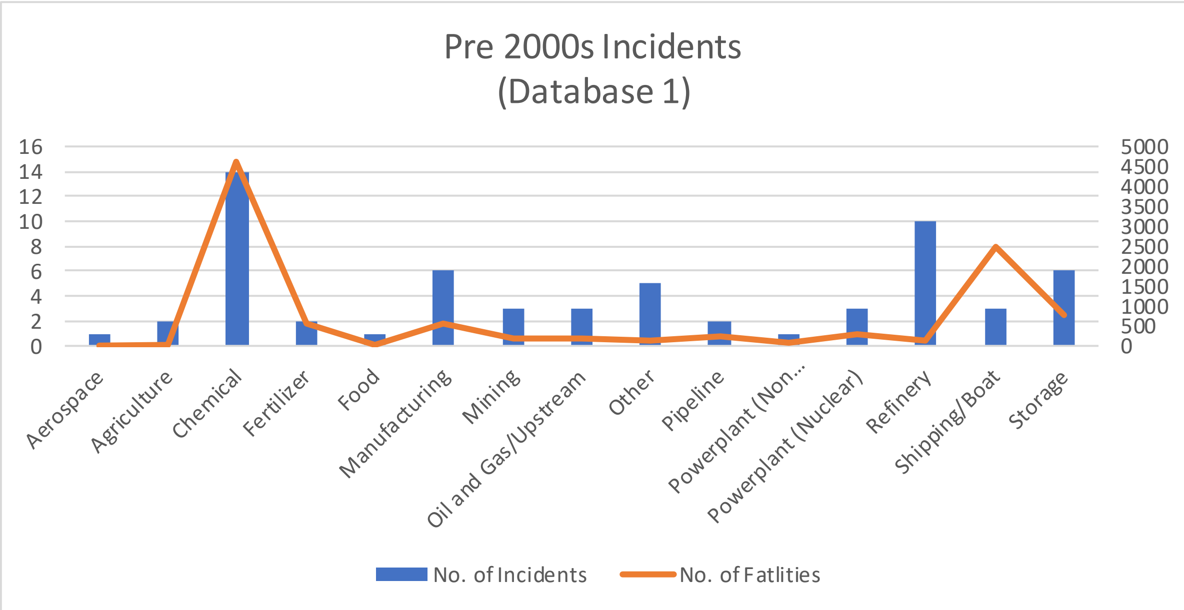

Figure 8: Relation of number of incidents and fatalities with type of operation in pre-2000 incidents from Database 1

Earlier studies on this topic showed that SC, emergency response and preparedness, MI, OP, and PHA as some of the most common root causes [1,2,4]. This study also saw analogous patterns in root causes with SC, PM, PHA, and OP being the four most common factors from Database 1 which can be seen in Figure 9. Similarly, the incidents investigated by the CSB and listed in Database 2 saw PHA, OP, Design, and PM as the most frequent root causes which is evident from Figure 10, whereas in Database 3 MI, OP, PM, and PHA were the most prominent factors in hydrocarbon industries as shown in Figure 10. Safety culture can be seen as a root cause of many process safety incidents; however, it was noticed that SC was weaker in developing nations than compared to developed ones, which should not be surprising. This includes non-technical issues like lack of knowledge of previous incidents, not considering safety as the topmost priority, and so on.

The Marsh Report consisted of a noticeable number of incidents initiated due to natural calamities like earthquakes, floods, etc. For example, in 2018, a 7.5 magnitude earthquake struck Komo, Papua New Guinea, leading to extensive damage to Exxon's gas processing plant. Similarly, the flash floods of 2013 caused several disruptions in the La Plata Refinery

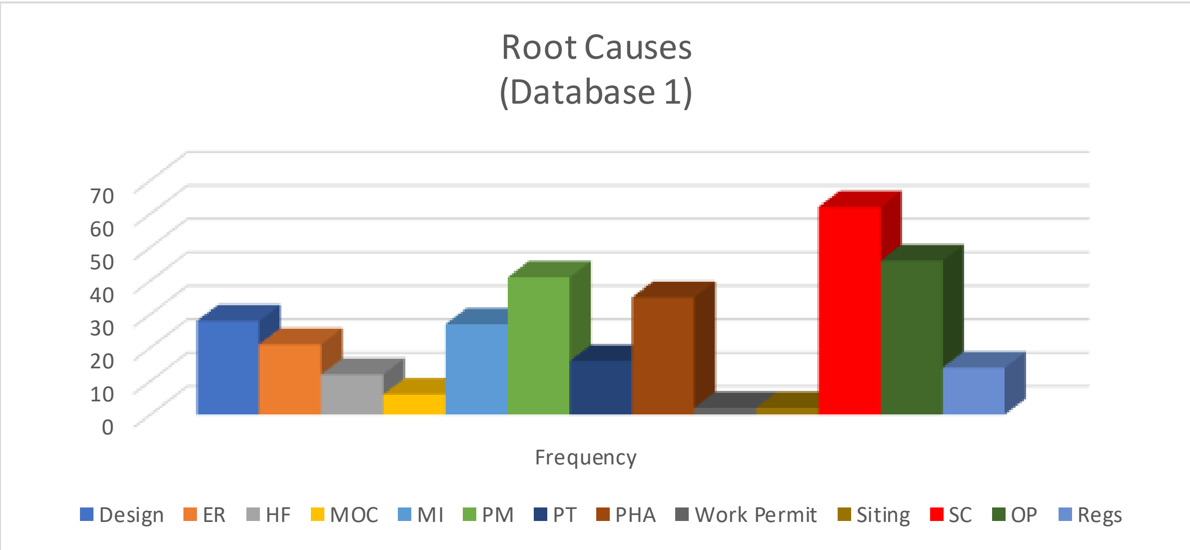

Figure 9: Most repeated root causes in Database 1

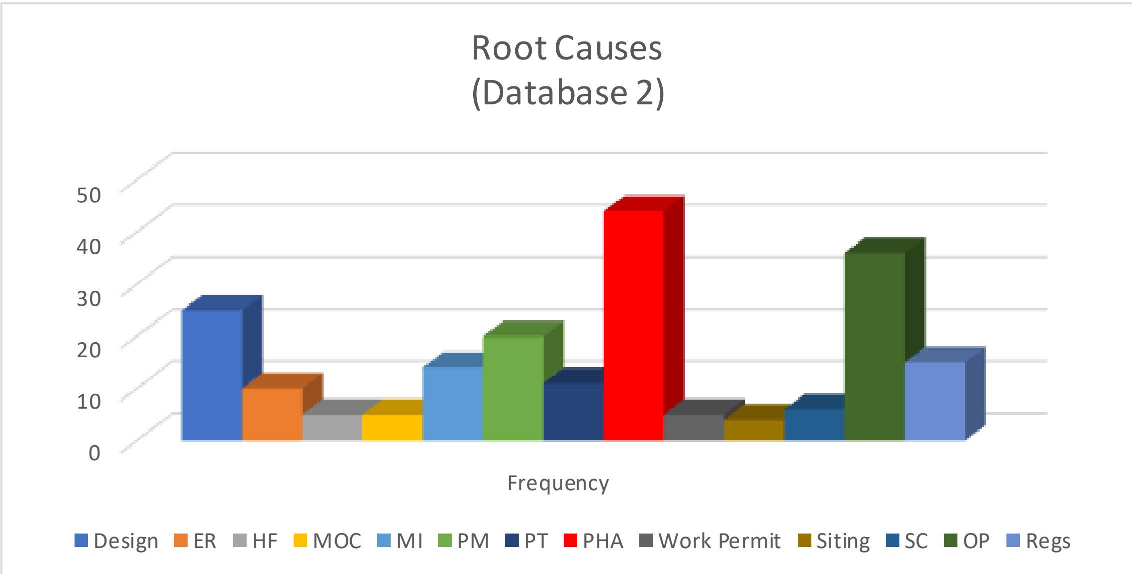

Figure 10: Most repeated root causes in Database 2

of Argentina, including explosions and fire in the crude distillation unit, as hydrocarbon mixtures entered the facility with the floodwater. Incidents like these create many questions while selecting site locations. Hence, natural disasters should be taken into consideration while constructing a facility as certain locations are more prone to such calamities.

A common trend can be noticed when the root causes of incidents are categorized based on the type of industry, as shown in Figure 12. From Database 1, it was observed that apart from

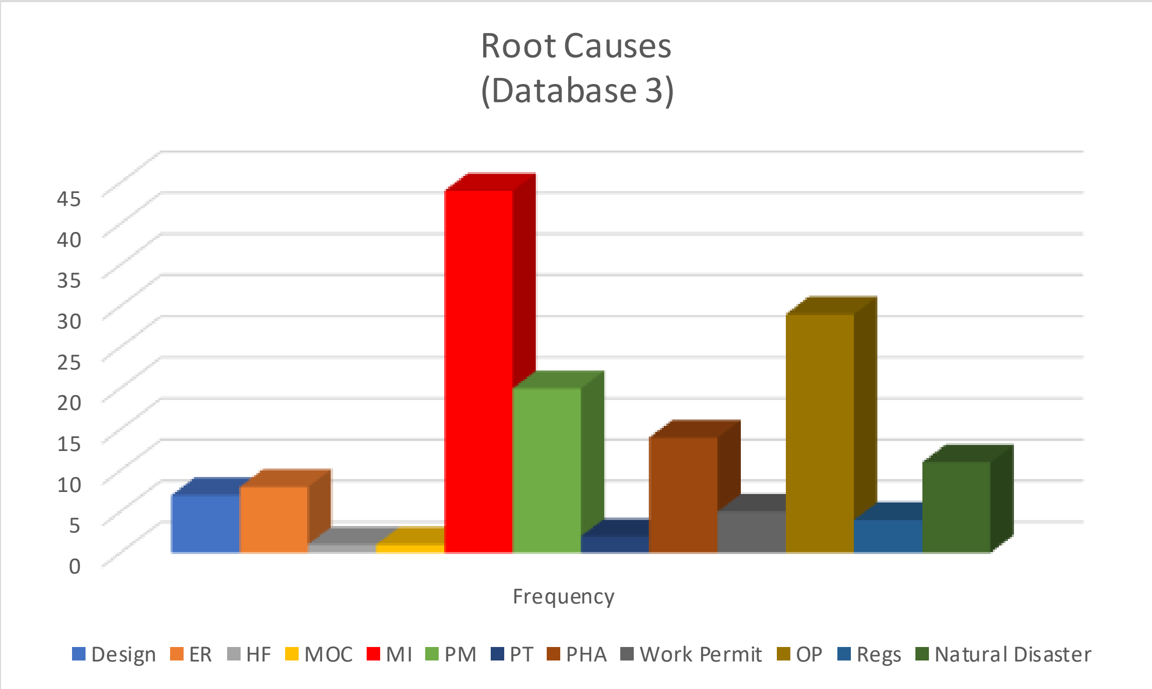

Figure 11: Most repeated root causes in Database 3

SC; PHA and OP were the most frequent root causes seen in incidents that occurred in chemical industries, while refinery setting saw MI and PM as major factors as per Figure 12.

Likewise, the manufacturing sector saw Design and Regs as the most common root causes, whereas incidents that occurred in storage facilities had PM and MI as the most repeated root causes apart from SC. This analysis of Database 1 was consistent with that of Database 2. Compared to hydrocarbon industry incidents listed in Database 3, it was seen that the refining sector had MI, PM, and OP as the top three most common factors from Figure 13.

Likewise, Figure 14 shows that the upstream industry saw MI, OP, and PHA as the more iterated in Database 3. Preventive maintenance and mechanical integrity can be seen as intertwined with each other. For example, a pipe rupture is often caused by loss of strength due to corrosion, external damage, or abnormal operation. The former two factors fall under the umbrella of 'Mechanical Integrity' and those can be mitigated if adequate and timely maintenance is carried out. Hence, both the root causes are dependent on each other.

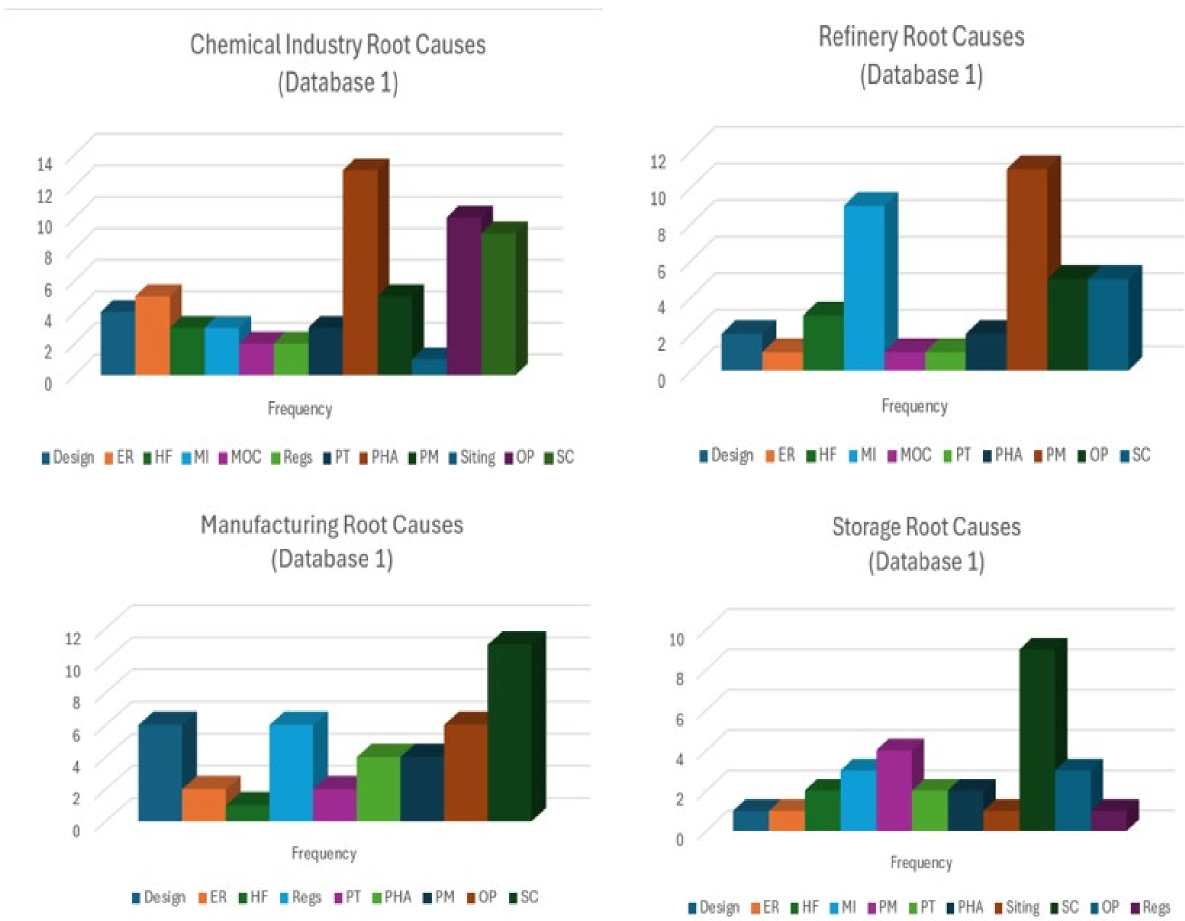

Figure 12: Most common root causes according to type of industry (Database 1)

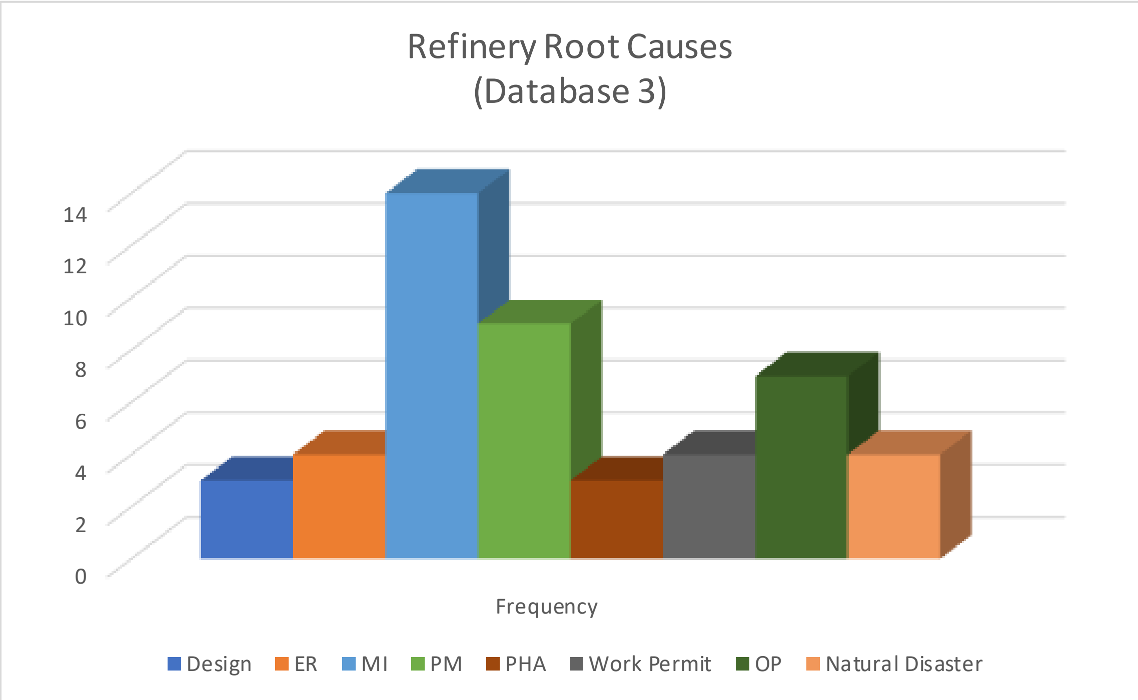

Figure 13: Most common root causes in Refineries (Database 3)

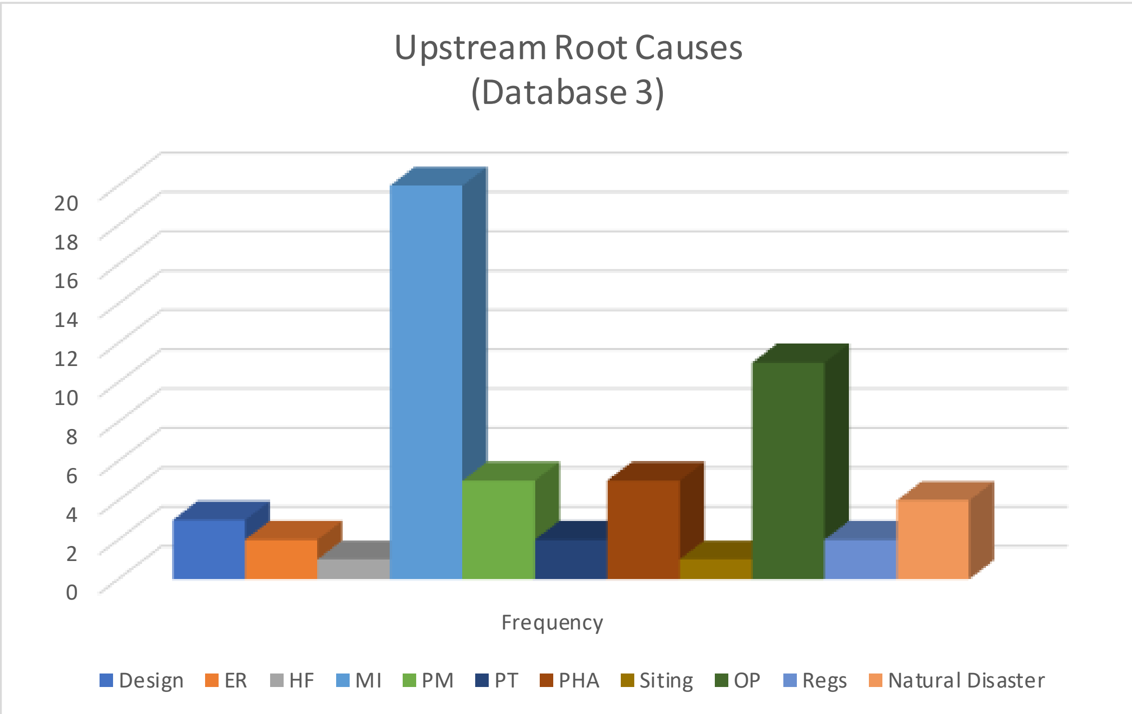

Figure 14: Most common root causes in the upstream sector (Database 3)

The incidents that occurred before the year 2000, also saw a similar pattern in the type of root causes with MI, OP, PHA, and PM being the most common factors, apart from SC, which can be seen from Figure 15. As time progressed and regulations got stricter, the safety culture also improved as the number of incidents occurring due to it decreased (this trend can be seen in the US and Europe). However, there is still scope for improvement.

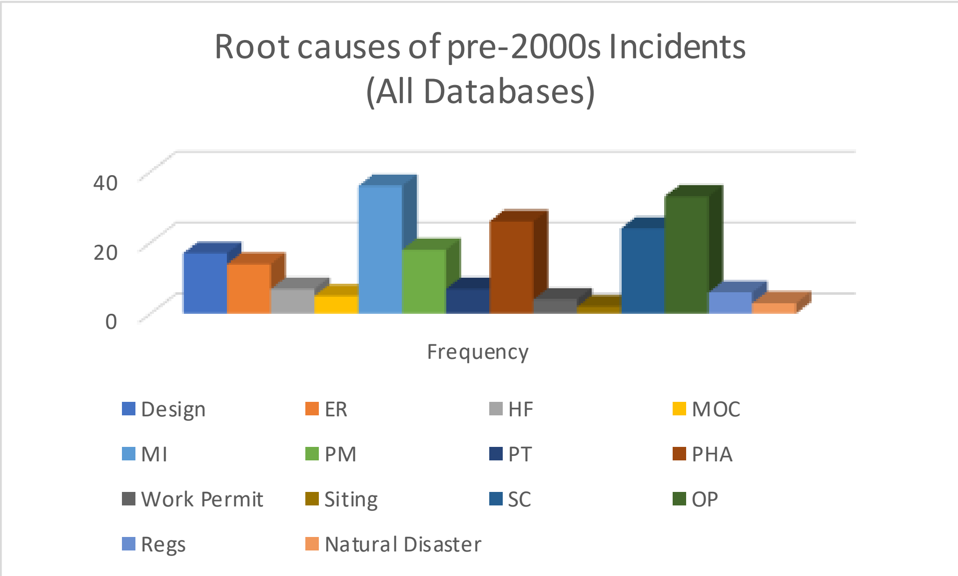

Figure 15: Most repeated root causes seen in incidents occurring before 2000 for all three Databases

Figure 16 shows the trends in root causes of incidents occurring after the year 2000, where results are similar to those seen in Figure 15. However, in this figure, there are noticeable instances where 'design' is one of the root causes of the incident. Such similar patterns suggest that immediate steps toward improving the existing process hazard assessments (PHAs), providing crystal clear operating procedures, carrying out routine maintenance, etc should be taken. In many instances, it was observed that industry personnel deviated from following the SOPs (Standard Operating Procedures). Hence, personnel training also plays a major role in this.

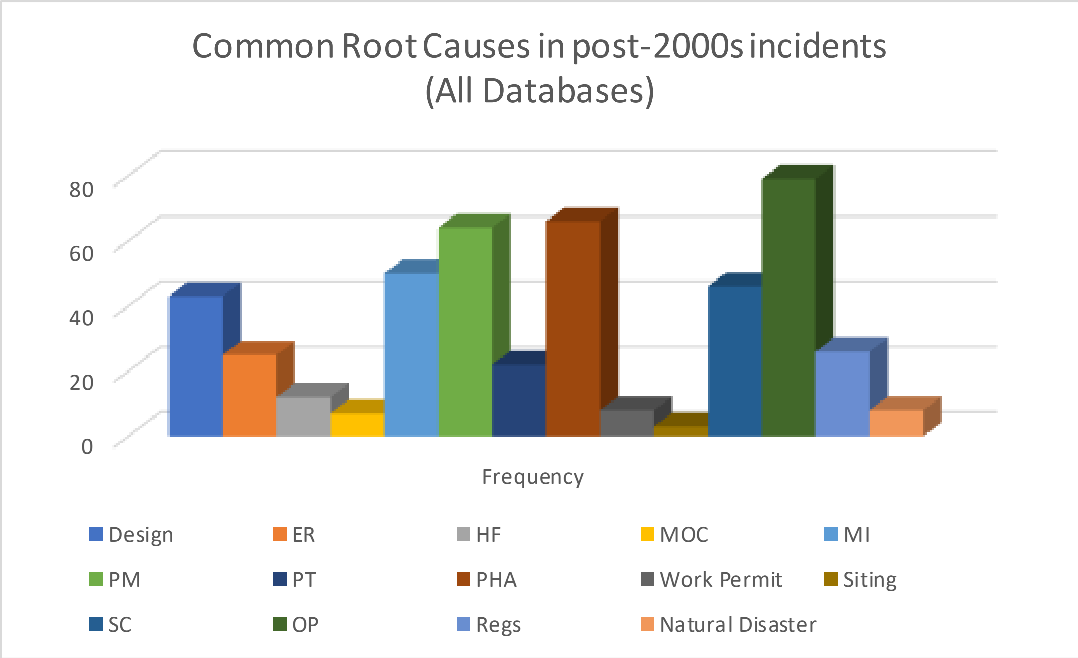

Figure 16: Common root causes seen in incidents occurring after 2000 for all databases.

Table 2 shows the most common factors contributing to incidents in their respective industries. These are the root causes seen in the analysis of 331 incidents from all the databases. In Table 2, to simplify the analysis, Gas Processing, Petrochemicals, and Terminals /Distribution incidents from Database 3 were categorized into Oil and Gas/Upstream, Chemical, and Pipeline sectors respectively.

Table 2: Common contributing factors seen in incidents as per the type of industry.

Type of RC	**TYPE OF OPERATION**						
	Aerospace	Agriculture	Chemical	Fertilizer	Food	Manufacturing	Sum
Design	✓	✓	✓			✓	4
ER			✓		✓	✓	3
HF		✓	✓			✓	3
MOC			✓	✓			2
MI	✓		✓				2
PM		✓	✓		✓	✓	4
PT	✓	✓	✓		✓	✓	5
PHA			✓	✓		✓	3
Work Permit		✓					1
SC	✓	✓	✓	✓	✓	✓	6
Facility Siting			✓				1

OP	✓	✓	✓	✓	✓	5
Regs		✓			✓	2
Natural Disaster						0

Type of RC	**TYPE OF OPERATION**					
	Mining	Oil & Gas/ Upstream	Other	Refinery	Powerplant (Non-Nuclear)	
Design	✓	✓	✓	✓		4
ER		✓	✓	✓	✓	4
HF		✓	✓	✓		3
MOC	✓			✓		2
MI		✓	✓	✓		3
PM		✓	✓	✓	✓	4
PT		✓		✓		2
PHA	✓	✓	✓	✓		4
Work Permit		✓		✓		2
SC	✓	✓	✓	✓	✓	5
Facility Siting		✓				1
OP	✓	✓	✓	✓	✓	5
Regs	✓	✓	✓			3
Natural Disaster		✓		✓		2

Type of RC	**TYPE OF OPERATION**				
	Power Plant (Nuclear)	Pipeline	Shipping/Boat	Storage	
Design	✓			✓	2
ER	✓	✓		✓	3
HF			✓	✓	2
MOC					0
MI		✓		✓	2
PM		✓		✓	2
PT	✓	✓		✓	3
PHA	✓	✓	✓	✓	4
Work Permit		✓			1
SC	✓	✓	✓	✓	4
Facility Siting	✓			✓	2
OP	✓	✓		✓	3
Regs			✓	✓	2

Natural Disaster	✓	✓	2

Abbreviation: ER: Emergency Response, HF: Human Factors, MOC: Management of Change, MI: Mechanical Integrity, PM: Preventive Maintenance, PT: Personnel Training, PHA: Process Hazard Analysis, SC: Safety Culture, OP: Operating Procedure, REGS: Regulations and Regulatory Oversight

Table 3, which is derived from Table 2 shows the total number of industries impacted by each root cause from the dataset of 14 different industries.

Table 3: Number of industries impacted by common root causes

Root Cause	Number of Industries impacted
Design	10
ER	10
HF	8
MOC	4
MI	7
PM	10
PT	10
PHA	11
Work Permit	4
SC	14
Facility Siting	4
OP	13
Regs	7
Natural Disaster	4

As seen in Table 3, safety culture seems to be the leading root cause of all process safety incidents across industries. Some of the examples include the Tianjin explosions of 2015 in China, where 800 tonnes of ammonium nitrate detonated due to unsafe storage practices which resulted in the loss of 173 lives, along with $1.1 billion in property damages and penalties. Weak safety culture was also seen in the US. One example is the 2021 acetic acid release in La Porte, Texas caused the deaths of two employees and property damages of $40 million [7].

Likewise, operating procedures and process hazard analysis (PHA) were the second and third most common root causes respectively. A 2008 propane explosion in Canada due to non-existent operating procedures and following illegal practices resulted in the loss of two personnel [7]. Similarly, the Fukushima Daiichi nuclear disaster in Japan in 2011 caused a huge loss of life and property, where it was found that the facility did not take into account the possibility of such a large tsunami while conducting the risk assessment [7]. A study on incidents investigated by the CSB also found insufficient operating procedures as a major concern in 44% of incidents listed in the database of 64 CSB incidents [4]. Hence, this is a clear sign of the requirement for better practices in terms of clear operating procedures and personnel training.

Design, mechanical integrity, preventive maintenance, etc were also some of the more prominent root causes observed in this analysis. A large proportion (59.5%) of the hydrocarbon industry incidents listed in Database 3 had mechanical integrity as one of the contributing factors. An explosion at Visakha Refinery, India in 1997 which resulted in the death of 56 individuals, and property damages of $15 million, was caused due to a leak of hydrocarbon from a pressure vessel [7]. Design was seen as a major root cause of nuclear powerplant incidents. For example, the Chernobyl nuclear incident which caused the deaths of 31 people (as mentioned earlier this number represents the number of immediate fatalities) and property damages of more than $100 billion, occurred due to inefficient design and PHA[7,10]. It is noticeable that mechanical integrity is the less prevalent root cause across 14 industries compared to many others, however, it has been a contributing factor in a large proportion of incidents.

Many process safety incidents are associated with impacting human life and/or property. This study also considered the additional cost apart from rebuilding the facility, this includes costs associated with compensations, penalties, and settlements. An effort was made to get accurate cost figures; however, as mentioned earlier, the scope of this study was limited due to a variety of factors. Figure 17 shows that the economic damage of 17.09% of total incidents listed in Database 1 fell between $1 million and $50 million, while 15.83% of the incidents had economic damage between $50 million and $200 million. 11.4% of incidents in Database 1 caused a monetary impact greater than $1 billion. For the incidents listed in Database 2, around 16% had impacts that cost between $1 million and $50 million. The incidents listed in Database 3 had a relatively greater economic impact, with 55.4% of incidents causing damages between $200 million and $1 billion, and 43.25% of incidents causing impacts of more than a billion dollars. As seen in Figure 17, there were no incidents in Database 3 i.e., Marsh report having damages of less than $50 million, even though the cost is not adjusted to present-day value. This shows the ruinous economic impacts of incidents that occurred in hydrocarbon industries. Of course, their database was designed to reflect the most impactful incidents. It was also noticed that apart from nuclear power plants incidents that occurred in chemical industries were the most economically impactful. This trend was consistent with both Database 1 and Database 2, while the upstream sector had the most economically damaging incidents in Database 3. Nuclear incidents like the Chernobyl disaster and Fukushima Daiichi accident have been some of the most financially expensive incidents which resulted in losses of over $100 billion [7]. Similarly, upstream incidents like the Deepwater Horizon (Macondo) incident which was caused by the failure of the blowout preventer (BOP), resulted in the loss of 11 personnel and cost around $65 billion, being one of the most impactful oil spills [11]. Effective emergency response plays a vital role in limiting the damage after an incident has occurred. It was seen that inadequate measures taken after the upstream incidents led to extensive damage. This also indicates proper training of the personnel and risk management. In this analysis of monetary damage, for around 39.4% of the total 331 incidents, comprehensive data was not available. Hence, such incidents are depicted in Figure 17 under the 'NA' category.

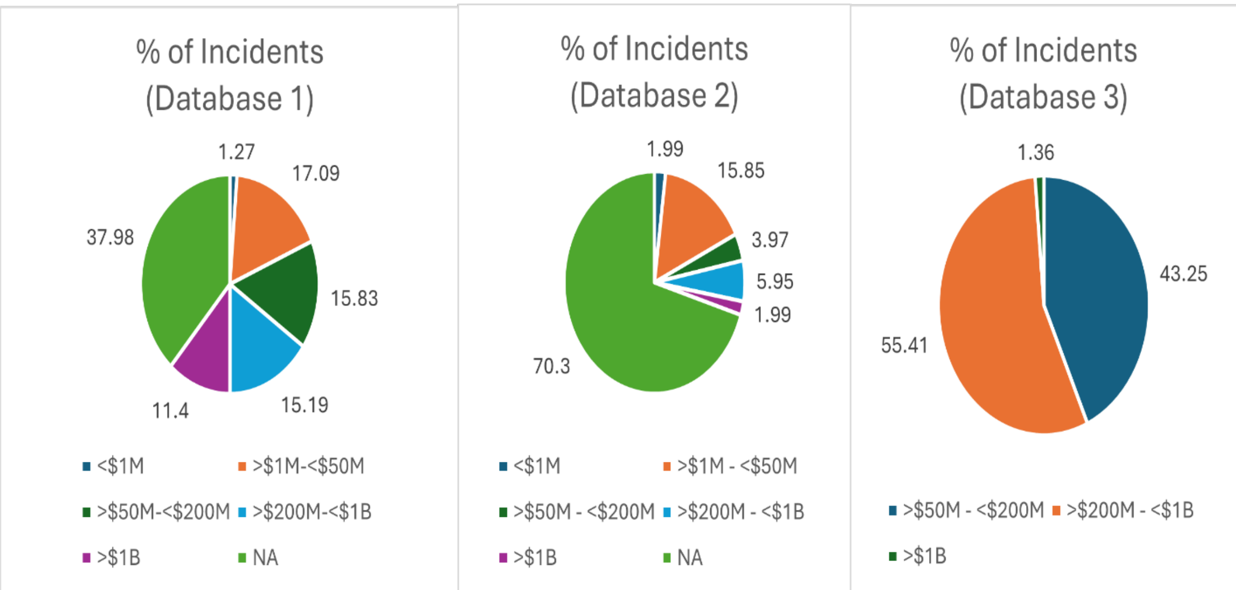

Figure 17: Economic damage of incidents listed in all Databases

It was seen that incidents in which explosions were involved, often occurred due to the formation of vapor cloud, fine metal, or combustible dust dispersion. The latter two types are more prevalent in the manufacturing and agriculture sectors. In chemical and fertilizer industries, a noticeable number of explosions occurred due to runaway reactions, which led to over-pressurization in the vessel. BLEVE (Boiling Liquid Expanding Vapor Explosion) is also a major type noticed in oil, gas, and petrochemical industries.

This decade has seen an increase in dust explosions mainly in the metal alloys, batteries, or related manufacturing sector, with the latest explosion occurring in Jiangsu Province of China earlier this year, resulting in eight deaths [12]. Another accident occurred in a battery manufacturing facility in South Korea, where a fire broke out in the battery storage facility leading to 23 casualties [13]. Apart from explosions, dust of toxic metals like lead can cause severe inhalation problems and may even cause death [14]. In most cases of dust explosions, it was noticed that the employees were unaware of the hazard or had limited knowledge. As a result, personnel training and emergency response play a vital role in such situations. Hence, it is necessary for industries to provide proper training to employees and educate them on hazard identification and response strategies. Also, the industries need to be equipped with up-to-date detection systems, proper ventilation, and adequate layers of protection to mitigate such incidents.

CONCLUSION

Process safety incidents are catastrophic events that can bring severe damage to human life, property, and the environment. Such incidents have also caused a variety of social and psychological effects on people, and with the onset of the industrial revolution, these incidents have become more frequent, especially in developing countries, hence it becomes necessary to prevent them by imparting knowledge available from previous incidents. As mentioned earlier, such incidents cause monetary damages worth millions and, in some cases, even billions of dollars. More than two-thirds of the total incidents listed in this analysis have caused public impact. This analysis covered incidents across a range of industries and one can gain more insights on the most common root causes prevalent in the given set of industries and operations. It was seen that safety culture, operating procedures, process hazard assessment, and mechanical integrity were the most common root causes in 331 incidents studied. This does not mean that other contributing factors are less relevant. However, it was observed that the most severe incidents had the root causes which were related closer to the human aspect of process safety, which involves promoting safety, following proper procedures, identifying hazards, and taking adequate measures to prevent the incident altogether. This is a clear indication that those incidents could have been avoided if safety was given the topmost priority.

Hence, this analysis can be useful to a range of industries as it includes a diverse set of incidents. Industry stakeholders can utilize these results and learnings from history to improve areas where other industries have lagged.

FUTURE WORK

The results and findings of this study should be shared with a large audience, to spread awareness and educate stakeholders at all levels, from frontline workers to top management. This will provide new opportunities to explore and adopt new practices in process safety. By learning from the past, industries can implement measures to eliminate these risks, thereby enhancing overall safety. Moreover, improving existing safety practices based on these findings can help in significant advancements in operating procedures and response strategies.

This is a dynamic study, where results will change as the database gets bigger with more incidents reported. As mentioned earlier, many incidents most likely go unreported, hence awareness should be spread regarding this matter. To achieve these objectives, regulatory bodies and industries must collaborate closely. Regulatory bodies play a crucial role in establishing and enforcing safety standards, while industries possess real-world knowledge and data from their operations. By working hand in hand, these entities can ensure that incident information is shared transparently and comprehensively. The most important aspect of all is to recognize the need for improvement and commit time and resources for improvement.

Ultimately, the goal is to leverage lessons learned from past incidents and create a safe working environment. Through effective communication, collaboration, and continuous improvement, industries can move towards a future where accidents are minimized, and safety is prioritized.

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APPENDIX

- Database 1 (156 global incidents):

  https://docs.google.com/spreadsheets/d/1NcyTbiBIh-GzlILNE13wxDIKJlGYhMWkhw_KYOZ3dY4/edit?gid=0#gid=0

- Database 2 (101 CSB incidents):

  https://docs.google.com/spreadsheets/d/1zBNy4iC4vBW-notsN57B081ZsWILQUFuYQs7U2VsytE/edit?gid=0#gid=0

- Database 3 (74 Marsh Incidents):

  https://docs.google.com/spreadsheets/d/1RpDjCPsQMjC_OEElLrRxrOAW_rKj_C2q8TZEDYN1RKA/edit?gid=0#gid=0

Tables:

- Table 1: Key root causes along with their definitions [8,9].

Sr No.	***Root Cause***	***Definition***
1.	*Safety Culture (SC)*	*CCPS defines safety culture as 'the common set of values, behavior, and norms at all levels in a facility or wider organization that affect process safety.' A weak safety culture implies a lack of leadership, a lack of a common understanding of everyone's responsibilities regarding safety, ineffective supervisory oversight, placing production before safety, ineffective safe management systems and not measuring proper personnel and process safety metrics.*
2.	*Hazard Awareness and Identification*	*The process of identifying the hazards in the workplace that can cause potential harm to personnel, environment, or processes and eliminating these hazards to reduce workplace incidents (e.g., ventilation and gas monitoring). This is a daily understanding of hazards across the workplace by the workforce, vs. higher level PHA. It is commonly done by a hazard assessment survey of operations, understanding of process safety information like safety data sheets (SDS), proper housekeeping for cleaner and safer workplace,*

		equipment and materials, and recording incidents and near misses.
3.	*PHA*	*PHAs (Process Hazard Analysis) use methodologies including but not limited to Checklist, What if, HAZOP (Hazard and Operability) study, and FMEA (Failure Mode and Effects Analysis). They are commonly done by a team consisting of representatives of operations, engineering, and maintenance. In the US, compliance with OSHA PSM requires they be performed at least every five years. Observed shortcomings may be a lack of a PHA or inadequate/incomplete effort.*
4.	*Operating Procedures (OP)*	*Written operating procedures aligned with process safety that provide clear step-by-step instructions for safely performing tasks involved in each process. These typically include operating limits, safety and health considerations, and safety systems, for multiple operating modes - initial start-up, normal operations, shutdown et al. as noted by OSHA PSM.*
5.	*Work Permit System*	*A work permit system is a formal written system used to control certain types of work (e.g., lockout/tagout, hot work, work at height, or confined spaces) that are not part of routine operations and are potentially hazardous. The document typically specifies the work to be done and the precautions to be taken to mitigate hazards, reviewed and signed off on by site supervision. Observed shortcomings may include an absence of a system, documented inadequacies not remedied, and incomplete execution of an existing system.*
6.	*Personnel Training (PT)*	*A comprehensive on-the-job training (OJT) program and informative/technical training of employees and contractors (including supervisors). The program is documented and includes periodic refresher training and assessment of competency. Emergency response duties and training for response are included for relevant personnel.*
7.	*Mechanical Integrity (MI)*	*Companies design mechanical integrity programs to help determine the acceptable level of risk, engineering design standards, and the need for refurbishment/replacement as equipment reaches its useful life. The inspection, testing, and maintenance of process equipment typically consider the hazards and risks of the operations, including such equipment as vessels, storage tanks, piping systems, relief systems, controls, alarms, and emergency shutdown systems. Examples of excellence include a documented mechanical integrity program with written procedures*

		and a schedule for inspections and testing to ensure fitness for use during the equipment's lifetime.
8.	*Safeguards, Controls & Layers of Protection*	*Barriers, such as instrumentation and control hierarchy, are designed to address potential failures. Note that every safety device has a probability of failure on demand. Failing to function on market for a safety device such as a ruptured disc, PRV, secondary containment, etc. or backup power generator would constitute inclusion in this category.*
9.	*Preventive Maintenance (PM)*	*Preventive maintenance is the periodic inspection and maintenance of equipment to reduce the likelihood of failure or performance degradation. This is to determine that the equipment is safe to operate and to fix issues thus preventing major hazards due to equipment malfunctioning.*
10.	*Management of Change (MOC)*	*CCPS defines Management of Change (MOC) as a process to ensure changes do not inadvertently introduce new hazards or unknowingly increase the risk of existing hazards.' MOC includes a review and authorization process for evaluating proposed adjustments to facility design, operations, organization, or activities before implementation to make certain that no unforeseen new hazards are introduced and that the risk of existing dangers to employees, the public, or the environment is not unknowingly increased. Observed shortcomings may be a lack of an MOC process, an existing process but not utilized, or an inadequate/ incomplete process.*
11.	*Contractor Management*	*The expectation is that operators will consider safety performance and related training in the selection of contractors. The contractors in turn are expected to arrive on-site knowledgeable of safe work practices and potential hazards associated with their assigned role.*
12.	*Design*	*Designs generally consider RAGAGEP (Recognized and Generally Accepted Good Engineering Practices), reflecting hazards, safety systems, and instrumentation. Shortcomings may include an inadequate facility design, materials of construction, or lack of appropriate safety systems or barrier protection. Lack of consideration of potentially safer design.*
13.	*Human Factors (HF)*	*Human and organizational issues, such as equipment-related (e.g., valve location, lighting), sufficient staffing, as well as broader organizational issues. Often seen in terms of the interface between individuals, equipment,*

		and systems/procedures. Shortcomings can result in accepted 'normalization of deviance' by operators.
14.	*Facility Siting*	*Proximity of facilities to the public (i.e. residential housing, educational facilities, shopping areas, etc.), as well as the location of onsite plant personnel to hazards. Considers analysis of consequences of flammable and/or toxic hazardous materials.*
15.	*Pre-startup Safety Review*	*Before restarting a facility the expectation is that a process will be followed to review the changes made, that they are per specifications, that any PHA recommendations were followed, and that employees/contractors have received related operator training associated with any changes.*
16.	*Regulations and Regulatory Oversight (Regs)*	*There are a variety of regulations (e.g., OSHA, EPA, DHS) that cover people in and outside a site, as well as the environment. This may include periodic regulatory inspections/audits. An example of a shortcomings may be failure to meet inspection/audit expectations. Regulations typically set a minimum standard for compliance, so there may be areas or issues not necessarily covered by a specific regulation.*
17.	*Natural Disasters*	*Natural disasters such as earthquakes, hurricanes, and lightning can initiate catastrophic events. Designs and procedures should consider severe weather events such as hurricanes, earthquakes, 100-year floods, etc. This is separate and different from emergency response following an incident. This factor would be selected if there was a natural weather event involved, or if there was a documented failure to design for that event.*
18.	*Emergency Preparedness and Response (ER)*	*Equipment, processes, and training should generally be capable of handling emergencies such as spills, fires, explosions, natural disasters such as hurricanes, and security breaches. Examples of excellence include written procedures, defined teams with clear roles, and periodic training and drills, which may include appropriate external parties.*