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Analysis of severe industrial accidents caused by hazardous chemicals in South Korea from January 2008 to June 2018

Seungho Jung[a], Jongkwon Woo[b], Chankyu Kang[c,*]

[a] Ajou University, Department of Environmental and Safety Engineering, Worldcupro 206, Yeongtong-gu, Suwon 16499, Republic of Korea
[b] Korea Occupational Safety and Health Agency, Major Accident Prevention Division, 400 Jonggaro, Jung-gu, Ulsan 44429, Republic of Korea
[c] Ministry of Employment and Labor, Chemical Accident Prevention Division, 422 Hanruridae-ro, Sejong 30117, Republic of Korea

ABSTRACT

Major accidents in the chemical process industries are relatively rare, but the resulting harm to workers, property loss, business interruption, and the environment are very serious. This study investigates chemical accidents that occurred between January 2008 and June 2018 in South Korea, and proposes ways to prevent similar accidents from occurring by analyzing the main causes of these accidents. Nine core concepts were drawn from the analyses comparing chemical accidents in South Korea: (1) current casualties by type of worker, (2) how the scale of the enterprise affects the disaster, (3) chemical accidents by type of occurrence, (4) analysis of ignition sources, (5) chemical accidents by CPI facilities, (6) human and technical error, (7) chemical accidents by work situation, (8) chemical accidents by non-compliance of process safety management (PSM) standards, and (9) chemical accidents by hazardous materials. Although there have been no recent occurrences of large chemical accidents since 2017 due to various factors, our results indicate that the past frequency of such accidents area serious concern in South Korea. Understanding the root causes of these accidents can help to prevent the recurrence of similar accidents and to strengthen preventative measures in chemical plants.

1. Introduction

The aviation, maritime, nuclear, healthcare, and chemical and petroleum processing industries are all highly-dependent on technology and have become increasingly complicated since the development of automation and sensor technology (Crowl and Louvar, 2011; Zhang et al., 2017). While these complex and sophisticated systems (i.e. non-linear complex systems) are economical and efficient, they can also lead to disastrous failure when they are not working properly (Khakzad et al., 2018; Al-shanini et al., 2014). While this technological revolution has contributed to an exponential increase in industrial activities, it is also linked to an increase of industrial accidents (Broughton, 2005).

Major chemical accidents have severe adverse impacts on human well-being and surrounding ecosystems, particularly insect and plant communities (Casal, 2017; Shen et al., 2015). As a result, scientific and public interest in chemical accidents has expanded and a considerable amount of research has been dedicated to identifying the various causes of and remediation for the accidents. Mihailidou et al. (2012) compared industrial accidents in developed and developing countries and found that while many industrial accidents occurred in the former, there were considerably fewer deaths and casualties than in latter due to a better enforcement of safety regulation legislation (Mihailidou et al., 2012). In a similar analysis of chemical incidents between 2012 and 2016, Wood (2017) showed that while a similar number of accidents occurred in both types of countries, developed countries had far fewer fatalities than developing countries. Salminen (2004) investigated the injury and fatality rate of workers in different age groups and reported that younger workers were more likely to get injured than their older counterparts because of lower technical skills, but had fewer fatalities. Duan et al. (2011) analyzed the causes and effects of chemical accidents caused by various hazardous chemicals in China from 2000 to 2006. Their analysis found that roughly 80% of dangerous chemical accidents occurred in small or medium-sized enterprises along the developed Southeast coast .

Lack of information and poor dissemination about accidents contribute to recurring incidents within this industry. This has led to many studies trying to identify the root cause of these accidents in order to inform suitable preventative measures (Gunasekera and de Alwis, 2008; Jacobsson and Akselsson, 2012; Moura et al., 2016; Vaughen and Muschara, 2011). Although most chemical accidents are known to have multiple causes (Nivolianitou et al., 2006; Sales et al., 2007), these often originate with human error, management decisions, single-point equipment failures or malfunctions, knowledge deficiencies, and management system inadequacies (The Center for Chemica Process Safety (CCPS), 2016). Kidam and Hurme (2013) found that 78% of equipment accidents were due to design and faults in human/technical interface. They analyzed 364 process equipment failures in Japan and found that 25% of the accidents occurred in piping systems, followed by human resources and organizational aspects (18%); fabrication, construction, or installation (13%); and layout (11%). Kidam et al. (2014) analyzed

* Corresponding author.
E-mail address: chemnet75@korea.kr (C. Kang).

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the BP Texas City Refinery explosion incident of 2005 and found that the process concepts, which included process conditions (i.e., contamination), reactivity, and incompatibility (i.e., unwanted reactions) made up 33.73% of the 83 design and operation-related errors. Hemmatian et al. (2014) analyzed 330 accidents of throughout the UK and EU countries and showed that while mechanical failure was the principal cause of accidents in developed countries, human errors and external events also caused many accidents throughout the world. The same study also found that chemical accidents occurring in the EU and the UK were caused by liquefied petroleum gas (LPG) (22%), gasoline (10%) and oil (9%). Reddy and Yarrakula (2016) analyzed 70 major process accidents in 30 countries across the world that were caused by hydrocarbons (55%) and toxic chemicals (30%). Of these, explosions (63%) and fires (25%) were caused by the flammable and explosive nature of hydrocarbons. Tarmimi et al. (2017) analyzed 770 cases of chemical accidents and claimed that these occurred due to design and technical errors (53%) and management (47%) (Bakar et al., 2017). However, despite these analyses, the problem of inaccurate accident reports and misinterpreted evidence has been raised. As a result, many accident databases have been created in multiple countries to minimize these problems (Mihailidou et al., 2012; Kletz, 2009).

Many activities are being undertaken and institutional improvements being made around the world to reduce the frequency of severe industrial accidents caused by leakage, fire, or explosion of harmful and dangerous substances (Lee et al., 2016). In 1982, the European countries adopted the Seveso Guidelines; the EU is currently revising and operating the Severe Directive. In the United States, the Occupational Safety and Health Administration (OSHA) established the Process Safety Management (PSM) standard in 1992 as 29 CFR 1910.119. The PSM standard, introduced in South Korea in 1996, has contributed significantly to the reduction and prevention of accidents in chemical plants. However, although the number of severe chemical accidents has remained stable since 2005, both large and small chemical accidents still have occurred in recent years (Fuentes-Bargues et al., 2017; Amyotte et al., 2016).

This study aims to analyze chemical accidents in South Korea caused by fire, explosion, and leaks from January 2008 to June 2018. According to International Labour Organization (ILO) Convention No. 174, a major accident refers to “an accident that causes damage to workers and nearby areas due to a major emission, fire, or explosion in the course of a major hazard installation involving one or more hazardous substances” (Prevention of Major Industrial Accidents Convention, 1993). Seventy-one cases of major industrial accidents were included for analysis in this study. This study aims to provide appropriate accident information about the chemical process industry (CPI) by analyzing nine core concepts drawn from the analyses. From these analyzes, we aim to identify the different causes of accidents and draw conclusions for their future reduction and prevention.

2. Analysis of major chemical accidents

2.1. Casualty between types of workers

Table 1 provides a detailed breakdown of the deaths of contract and subcontract workers caused by chemical accidents included in this study. In 2012, there were 15 casualties in major industrial accidents: the largest casualty count of the past 10 years. Chemical explosions and leaks in CPI plants caused the deaths, as well as property losses. However, there were fewer than 10 deaths annually—with the exception of 2012—as a result of strong government regulation and oversight after major accidents at CPI plants. Nonetheless, subcontract worker deaths continue to occur due to the outsourcing of dangerous work, mainly during repair and cleanup maintenance work at CPI plants. Such work is often dirty, dangerous, temporary, and irregular; as subcontractors are not familiar with the manufacturing process, they are more likely to die from exposure to high concentrations of hazardous chemicals (Satoh, 2009). A comparison of the number of deaths of primary contract and subcontract workers shows that, since 2013, the latter are significantly higher than the former. This trend changed after 2017, when the number of fatalities in subcontract workers decreased significantly due to an increase in public interest, resulting in improvements in both safety at the contract companies and governmental effort.

Table 1
Analysis of deaths from chemical accidents from January 2008 to June 2018.

Year	Number of accidents	Deaths of principal contract workers	Deaths of subcontract workers
2008	6	3	0
2009	4	1	0
2010	5	0	6
2011	3	9	0
2012	5	12	3
2013	5	1	6
2014	11	1	2
2015	11	2	6
2016	11	3	3
2017	4	0	0
2018.6	6	5	0

2.2. Effect of the scale of the enterprise

It is necessary to classify chemical accidents according to scale of the plant in which it occurred. Indeed, the larger the scale, the greater the number and types of equipment involved, and the larger the workforce. Fig. 1 shows the effects of company scale on the severity of chemical accidents, showing the related injuries and fatalities of principal contract and subcontract workers. In South Korea, CPI companies employing more than 100 workers have experienced a higher level of deaths and injuries. For example, 78% of deaths in principal contract workers occurred in medium (> 50 employees) and large-scale enterprises (> 1000 employees), while 92.3% of deaths in subcontract workers also occurred in similarly-sized companies. The reason for the high number of fatalities in companies employing 100–300 people is that rapid technological change has decreased the price of industrial robots and increased CPI automation (Michaels et al., 2014), leading to complicated and dangerous large-scale maintenance tasks being outsourced and resulting in an increased mortality in subcontractors. In fact, annual maintenance work in the oil and gas industry is known to cause major chemical accidents (Okoh and Haugen, 2013a).

2.3. Type of chemical accident

Fig. 2 illustrates the different types of accidents included in this study. A number of studies have shown that fires, explosions, and toxic substance leakages in CPIs generally occur in areas related to oil and gas storage tanks (Zheng et al., 2018). Explosions, fires, and toxic leakages caused 42.3, 29.6, and 28.1% of chemical accidents in South Korea, respectively, between 2008 and 2018. Explosions, fires, and toxic leakages caused 42.3, 29.6, and 28.1% of chemical accidents in South Korea, respectively, between 2008 and 2018. Despite being the least common cause, accidents caused by toxic leakage are still concerning, particularly due to aging of the large chemical industrial parks (Duan and He, 2015).

2.4. Ignition sources

Our previous analysis, which showed that fires and explosions caused a large number of disastrous accidents (71.9%; Fig. 2), led to a more detailed analysis of the ignition sources causing chemical accidents. A combination of static electricity (32.4%) and electric sparks (14.1%) accounted for 46.5% of all accidents, as shown in Fig. 3. As the

Classification	Type of Worker	Less than 50	50~100	100~300	300~1,000	More than 1,000
Death	Principal Contractor	8	4	16	8	1
	Subcontractor	2	0	12	3	9
	Sum	10	4	28	11	10
Injury	Principal Contractor	20	14	20	12	6
	Subcontractor	7	4	28	7	15
	Sum	27	18	48	19	21

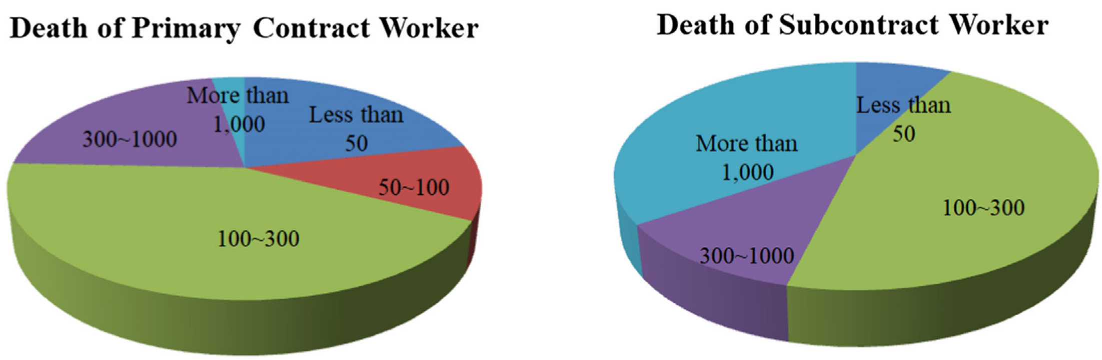

Fig. 1. Number of reported injuries and fatalities, according to the scale of enterprises.

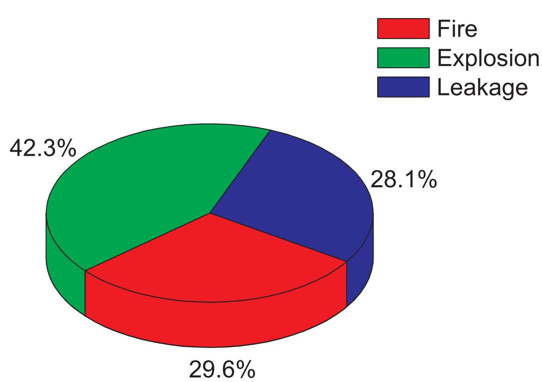

Fig. 2. The contributing causes of chemical accidents included in this study.

minimum ignition energy of flammable liquids and gases is very low (< 1 mJ) (Hurley, 2016); they can be ignited by static electricity produced in the process of transferring combustible liquids and gases, generated by a worker's body, or if an explosive atmosphere formed due to hot weather. Workers who operate or handle dangerous equipment and hazardous chemicals directly should take the following into consideration to keep static electricity at a minimum (Health and Safety Executive, 2015): (1) the use of conductive material, (2) restrictions in flow rate, (3) grounding and bonding, (4) submergence structure of transport piping, and (5) use of electrification gloves and clothes to remove static electricity from their bodies. In addition, 26.8% of chemical accidents were caused by the ignition of leaked flammable substances as a result of poor facility management.

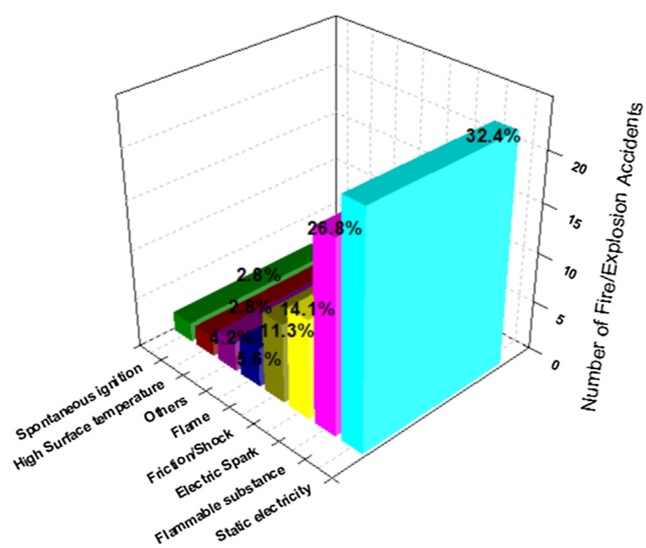

Fig. 3. Types of ignition sources for accidents caused by fires and explosions.

2.5. Failure of chemical facilities

Fig. 4 details the number of chemical accidents occurring in various CPI facilities within chemical plants. Most accidents in chemical facilities occurred in storage tanks (25.4%), followed by chemical reactors and mixing tanks (22.5%). Leakage accidents caused by failure of the pipes and valves occurred due to equipment defects. Many chemical accidents occurred during internal cleaning and inspection of storage

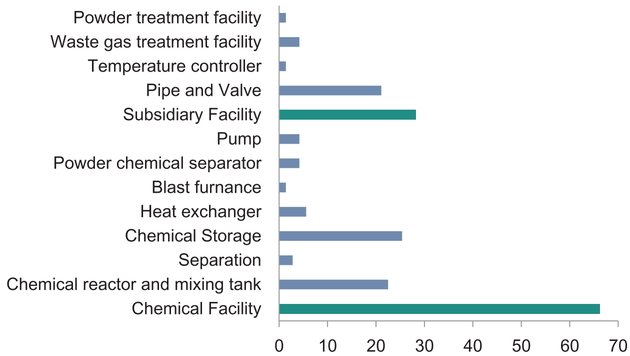

Fig. 4. Frequency of chemical accidents in different CPI facilities.

tanks from which internal hazardous materials had not been completely removed. In the cases of gas or pure liquid hazardous materials, the internal dangerous materials can be eliminated through a nitrogen purge, while sludge-like substances are more dangerous, because they cannot be completely removed, even after using a steam purge and nitrogen gas (Yanisko et al., 2011). Batch reactor accidents often occurred after solvent was injected through the manholes and created an explosive atmosphere. The resulting runaway reaction is a type of chemical accident where, even when a safety valve is installed, an explosion will occur if a rupture plate is not present. A case was reported where the rupture plate operated correctly, but the dangerous material discharged was not treated safely and escaped into the atmosphere. Generally, most of these runaway reactions occurred during normal operations, whereas accidents that occurred during commissioning were normally the result of workers failing to follow safe operation procedures.

2.6. Human and technical errors

Although many chemical accidents were caused by a combination of human and technical errors, the classification of errors in Fig. 5 shows the root cause of the accidents included in this study. Given that CPI accidents caused by human error are inevitable and harder to control, the majority of accidents occurring in South Korea resulted from human factors. Jahangiri et al. (2016) explained that human errors include the lack of a work permit, improper analysis of hazards, and inadequate training in the use of safety procedures.

Depending of the size of the chemical plant, small differences in the causes of accidents were observed. In large-scale plants, subcontract workers did not comply with safety work permit and procedure during maintenance and repair operations. Occasionally, safety work procedures had not been developed or were inadequate. Similarly, workers employed in small and medium-sized enterprises often failed to comply with the safety protocols, resulting in chemical accidents during normal operations. Technical errors caused by design defects, facility inspections and maintenance failures were fewer in comparison with human errors. Despite not causing as many casualties, chemical accidents caused by technical errors should not be overlooked.

2.7. Work situation

Chemical accidents occurred during normal operations (45.9%), maintenance work (30.9%), commissioning (9.8%), shipping and handling (8.4%), and shutdown processes (5.6%), as shown in Table 2. In small and medium-sized enterprises, many accidents occurred during normal operations (38.1%), as operational processes were not automated and dangerous chemicals were often handled by workers directly. In such cases, companies do not seem to foster a culture of safety and educate their workers about the potential risks of handling certain chemicals or performing specific operations. By contrast, employees in large-scale enterprises do not directly handle hazardous chemicals, as most of the processes are automated. However, they often employ subcontractors for maintenance tasks, who often lack the necessary expertise and experience to carry out tasks handling dangerous chemicals. The number of safety work permits during maintenance work at a chemical plant is very complicated, and there are many professional work contents. Safety managers often struggle to teach and implement rigorous safety protocols, as safety considerations change with the processes involved in the work task assigned, and they oversee a large number of employees.

2.8. Non-compliance of PSM regulation

As of June 2018, there were 2125 sites within which hazardous facilities manufactured, handled, and stored more than the threshold amount to be regulated under current PSM regulation as hazardous

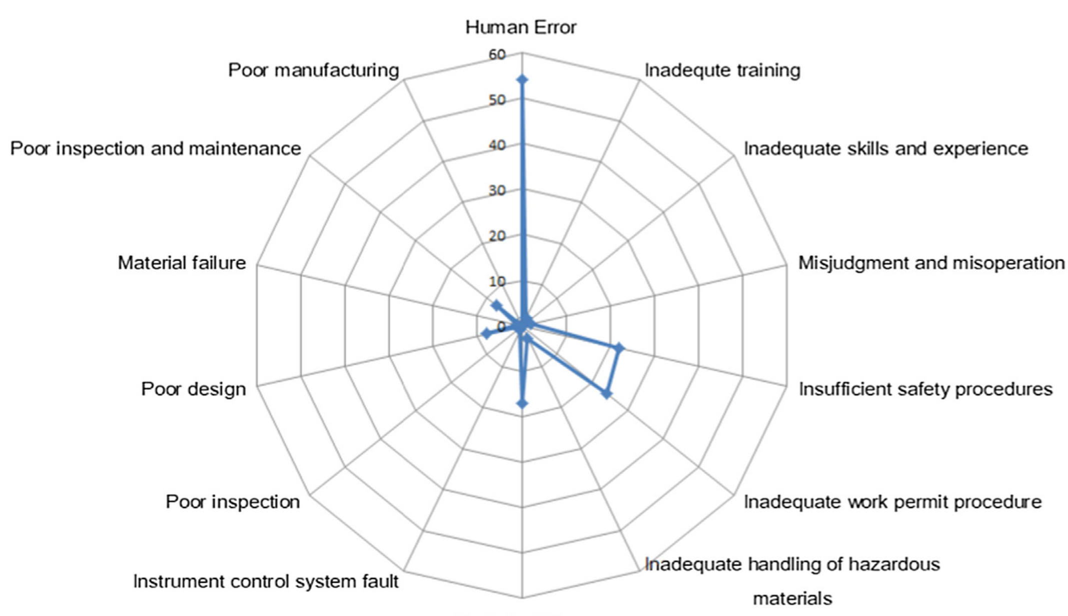

Fig. 5. Classification of human and technical errors.

Table 2
Chemical accidents during various work processes.

Number of employees	Commissioning (%)	Normal Operation (%)	Facility Maintenance (%)	Shipping and Handling (%)	Shutdown (%)
< 50	1.4	16.9	2.8	2.8	0
50–100	0	8.5	2.8	1.4	0
100–300	5.6	12.7	5.6	1.4	2.8
300–1000	2.8	2.8	7.0	0	2.8
> 1000	0	4.2	12.7	2.8	0
Total	9.8	45.1	30.9	8.4	5.6

substances. Those sites were distributed within seven chemical industries (e.g., crude oil refining, other petroleum refinery reprocessing business). In total, 51 types of hazardous substances are periodically evaluated for compliance with PSM safety regulations. In South Korea, this evaluation is based on the management criteria of 12 factors, with the pass (p-grade) being set at a score of 90 or higher. The results show that 50% of PSM-evaluated chemical plants are low-grade sites (i.e. M^+, M^- level), revealing a high risk of chemical accidents occurring due to operator mistakes caused by poor training, poor operating practices, and poor design of control systems (Kwon et al., 2015). Among the PSM plants, only 5.1% obtained the p-grade, with 28.2% reaching the next-best level of s-grade (80 or higher). It is therefore still necessary to improve safety protocols in the CPI to ensure compliance with PSM regulations.

Fig. 6 summarizes the violations of PSM regulations in South Korea. Many chemical accidents occurred when violations of both the guidelines for safe operation and approval for safe work permits had occurred. According to Bakar et al. (2017) in the USA, EU, Japan, and Malaysia, the most serious cause of chemical accidents was the failure to follow the process hazard analysis and the guidelines for safe operation. Possible reasons for the violation of safety guidelines may be a lack of willingness to implement PSM regulations in the workplace and the continuous increase of small-scale workplaces. In addition, violation of work permit approval by PSM facilities increased the number of simple repairs or replacements, which eventually led to disastrous accidents.

2.9. Accidents by hazardous materials

It was clear that the most common cause of chemical accidents in South Korea was the mishandling of flammable liquids (52.1%), as shown in Fig. 7. This is probably because flammable liquids are frequently used in the workplace and are not easily diluted after being released, increasing the likelihood of formation of an explosive atmosphere. After flammable liquids, chemical accidents were most commonly caused by acute toxic substances (14.1%), flammable gas (12.7%), corrosive substances (8.5%), oxidizing liquids and explosive

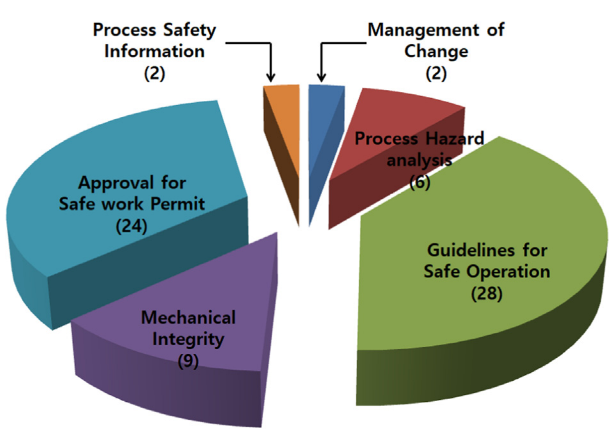

Fig. 6. Violation of PSM elements in cases of chemical accidents.

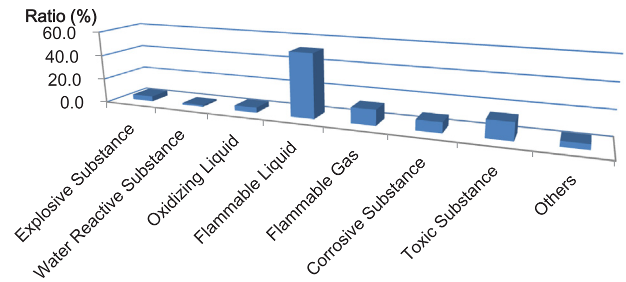

Fig. 7. Types of hazardous materials involved in chemical accidents.

substances (both 4.2%), and water-reactive substances (1.4%). Other causes caused 4.2% of chemical accidents. In recent years, several accidents caused by corrosive substances (e.g. hydrofluoric acid and sulfuric acid) and explosive substances ignited by static electricity have occurred. Intensive management would decrease the likelihood of other chemical accidents.

3. Case studies

Fires, explosions, and chemical leaks are still happening in chemical plants in South Korea, although the root causes and resulting damage for each incident differ. In this section, the types and causes of recent major chemical accidents are briefly described to help prevent future incidents of this nature.

3.1. Fires and explosions

In order for a fire or explosion to occur, the three elements of combustion must be present: a flammable material, oxygen, and an ignition source. At the Yeosu plant in 2013, workers were in the process of repairing a manhole; they drilled a hole at the lower side of the storage tank (silo) silo and high-density polyethylene (HDPE) dust remaining in the silo. The explosion occurred in the fuselage of the silo that was filled with air, and HDPE dust had attached to the sub-wall and the bag filter. During manhole installation, some dust was deposited on the lower side of the silo due to the pulsation caused by the vibration tool. Dust was ignited by welding sparks generated during manhole attachment welding, resulting in a fire and the subsequent explosion. Although the explosion was relatively small, it resulted in a large loss of life because many workers were present at the explosion site. In order to prevent similar accidents, it is recommended to thoroughly remove flammable materials from the inside the silo before maintenance work begins, and to check the dust level when issuing safety work permits. In addition, the plant installed explosion-proof equipment in silos and other containers handling flammable dust, so that explosive pressure could be discharged in a safe direction. Despite these precautions, however, fire accidents involving the silo bag filter occurred repeatedly in the same equipment.

3.2. Toxic leaks

An incident at the Gumi plant in 2012 occurred as a mobile tanker of anhydrous hydrofluoric acid produced in China was imported into South Korea. There was a leak during the process of producing 50 wt%, 55 wt% hydrofluoric acid, and five employees died due to exposure to high toxicity. Exposure to high concentrations of hydrofluoric acid lead to an increasing concentration of fluoride in the human body, decreasing calcium and increasing potassium levels in blood, which are ultimately leading to death fatal. This leak also caused serious health problems to on-site employees and nearby residents, also causing huge concerns on the environmental impacts of this leak. It was found that the valve to the anhydrous hydrofluoric acid leaked during preparation for the transfer to the dilution facility. One worker mistakenly stepped on the valve and – due to nature of the valve (i.e. a cock valve) – it opened easily. During the accident report, several violations such as non-compliance with the work rules were found, such as: lack of use of personal protective equipment, inappropriate wearing of protection equipment, lack of a leak prevention facility, inadequate valve type and lack of an alarm at the facility. In cases where non-compliance is indicated as the primary cause of an accident, it is necessary to set stricter protocols so that the hazardous substances do not leak. Unfortunately, the blind flange of the anhydrous hydrofluoric acid and air pipes are normally opened simultaneously. When connecting the air piping while supporting the handle of the anhydrous hydrofluoric acid valve with the feet, the valve did not support the weight of the worker and was opened unintentionally.

3.3. Chemical exposure

In 2016, an incident occurred during the phosgene manufacturing process at Yeosu plant: a worker wearing a gas mask (front type) was preparing for major maintenance work in the phosgene manufacturing chamber. When the bolt was loosened with the blind plate installed, as soon as the flange gap was opened the pressurized phosgene leaked into the pipe, killing the worker despite his mask. The use of the blind plate in the process of vent piping and the excessive shortening of the maintenance period were identified as the main causes of the accident. Another problem was that the issued work permit did not require the use of a portable gas detector to measure leakage on the piping or connecting parts, leading to gas measurement not actually being performed before or during the work. These technical deficiencies and systematic problems, as well as the chemical characteristics of phosgene, led to the worker's death. When inhaled, phosgene binds to water molecules in the lungs and is separated into carbon dioxide and hydrochloric acid. Hydrochloric acid causes symptoms such as dyspnea and pulmonary edema, which can be delayed by up to 24 h. As phosgene is colorless at room temperature and smells of dry grass, it is difficult for employees to recognize this chemical, and by the time symptoms appear, it is often too late.

4. Discussion

Although safety protocols are normally set up in chemical plants, chemical accidents still occur, as shown by this detailed analysis of accidents in Korean chemical plants from 2008 to 2018. The causes of accidents varied, but similar types of chemical accidents occurred repeatedly. These accidents are mainly caused by human errors but are closely related to the workers' solving ability and work proficiency. In addition, it seems to be due to lack of utilization and dissemination of safety information surrounding the occurrence and recurrence of chemical accidents (Salminen, 2004; Bakar et al., 2017; Jacobsson et al., 2011; Drupsteen et al., 2013). Additionally, the scale of the chemical plant seems to have a large impact on accidents, although this tends to vary from country to country. For instance, small-scale chemical plants in India are at higher risk of accidents due to weak environmental and safety regulations (Goh et al., 2015; Yang et al., 2015). In South Korea, principal contact workers suffered higher fatalities and injuries than subcontract workers in CPI plants employing < 100 workers. Even though they have relatively simple facilities compared to medium and large enterprises, it is estimated that the accidents are frequently happened because workers are mainly handled and used these facilities. In addition, many chemical accidents were caused by inappropriate handling of flammable liquids.

From a facility standpoint, many leakage accidents occurred in the pipe flange due to damaged gaskets; there were also accidents in which the bolts fastened to the flange were loosened due to excessive pressure or temperature changes during specific operation. In order to reduce costs and to increase safety and production, it is possible to systematically manage old facilities in CPI using risk-based inspection (RBI) technology, but this requires expert knowledge and training (Mohamed et al., 2018). Okoh and Haugen (2013b) found that chemical accidents due to maintenance received less attention; however, some major accidents were maintenance-related. Okoh and Haugen (2014) also analyzed 183 major accidents in the US and Europe and found that 80 cases (44%) were maintenance-related. Vinnem et al. (2007) investigated gas releases from the Norwegian offshore industry and found that more than 65% of major hydrocarbon leaks were caused by maintenance activities.

It is also known that the rate of severe chemical accidents caused by human error is increasing due to the complexity of processes within CPI plant (Kariuki and Lowe, 2006). For example, there are many kinds of control systems in CPI plants, depending on the production scale, the nature of chemical properties, automatic continuous production processes, and working methods to increase the possibility of the chemical accidents. Therefore, various kinds of accident prevention techniques aimed at preventing human error are being developed and implemented.

Today, chemical accidents involving errors in the human/technical interface are occurring more frequently than before. Kidam and Hurme (2013) analyzed 364 chemical accidents and found that faults in the human/technical interface were most common in piping systems, separation equipment, and heat transfer equipment. Also, an average of 2.5 factors combined caused chemical accidents. Nivolianitou et al. (2006) similarly argued that about 2.3 causes were combined after analyzing chemical accidents reported in the petrochemical industry.

5. Conclusions

Given the severe human, environmental, and economic impacts of chemical accidents, this study investigated various chemical accidents that occurred in South Korea from 2008 to 2018. In total, 76.1% of chemical accidents were caused by human error, highlighting the need to confirm safety work permits and safety protocols, since major accidents occurred during normal operations and maintenance processes. Small-scale enterprises experienced the most chemical accidents during normal operations, while large-scale enterprises experienced the largest number of industrial accidents during maintenance work. However, the number of technical errors was much less than that of human errors. This is in contrast to the leading causes of chemical accidents due to mechanical failures in developed countries and Europe. Many of chemical accidents occur repeatedly, underlining the severity of the problem. Experts are especially concerned by the fact that most deaths in plants employing > 100 workers involve subcontractors, while principal contractors should provide technical and safety guidance to subcontractors during large-scale maintenance work.

Fire and explosion accounted for 72% of all CPI accidents, of which 32.4% were ignited by static electricity. Chemical accidents in CPI facilities mostly occurred in storage tanks, chemical reactors, and mixing tanks. Successful accident prevention requires shorter inspection cycles and strengthening safety processes in CPI plants. In the process of cleaning storage tanks, one should ensure that hazardous materials are completely removed and that a nitrogen purge is thoroughly performed.

Case studies of fires, explosions, toxic leaks, and the resulting exposure in South Korea provided some valuable information. In order to prevent these similar accidents, the following preventive measures are necessary:

(i) To prevent explosions due to gas, vapor, mist, and flammable dust: the concentration of oxygen necessary for the composition of explosive mixtures must be suppressed and ignition sources must be shut off.
(ii) Flammables mixtures should be kept as low as possible to replace flammables with non-flammables to prevent further explosions.
(iii) Flammable gas detectors should be installed in potentially explosive areas and combined with other protective measures (e.g. emergency shut-off valves) to stop the process or unit during emergency detection.
(iv) In case of flammable liquid and flammable gas leakage, grounding and bonding should be thoroughly performed, and static electricity should be reduced as much as possible.
(v) In storage tanks, pipes, reactors, and silos, dangerous substances should be completely removed and the blanks installed to prevent the inflow of dangerous substances from the outside.
(vi) To prevent chemical accidents caused by human errors during repair, maintenance and normal operation, it is necessary to perform rigorous job safety analysis, operational procedures, and safety training to ensure compliance in chemical plants.
(vii) Use and periodically replace proper gaskets to protect the piping, flanges, valves, and cock joints to prevent leakage of hazardous chemicals.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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