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Research on Fire and Explosion Accidents of Oil Depots

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Fire and explosion accidents occurred frequently in oil depots in China which lead to great casualties, severe environmental pollution and large economic losses. Case studies of 435 fire and explosion accidents of oil depots in China from 1951 to 2013 are reviewed in this paper. From the analysis of time scale, area, facilities & equipment, ignition sources, types of accident substances, and responsibility, the statistic results show that the most dangerous area is the loading and unloading operation area, and the most vulnerable facilities & equipment are the storage tanks. Meanwhile, the proportions of ignition sources are so evenly distributed that the prevention of fire and explosion should be equally concentrated to several impact factors. The vapor cloud explosion could be the most common accident type in oil depots, and the management responsibility dominates in all of the accident causes. According to data analysis, special lessons learned from these accidents are proposed, and the majority of fire and explosion accidents in oil depots would have been prevented or avoided if security management had been improved.

1. Introduction

Oil depots including oil terminals or gas stations store a lot of flammable petroleum products. Once the fuel-air mixture or stored fuel is ignited, it may break out a large fire or explosion accident during the cleaning, antirust, spray-painting, storage tank maintenance, welding, loading or unloading works, etc, it may cause serious fire and explosion accidents in oil depots which lead to great casualties, severe environmental pollution and large economic losses. For the past few years, a series of large fire and explosion accidents were happened in oil depots all the world around, such as the Buncefield oil depot explosion in London (Mather et al., 2007; Devenish & Edwards, 2009), the Bayamon oil storage facility fire in Puerto Rico (Godoy & Batista-Abreu, 2012), and Indian Oil Corporation Ltd. explosion accident (Sharma et al., 2013). With the rapid economic growth and large petroleum consumption in China, fire and explosion protection becomes more and more essential to security management in oil depots as a result of continuous increasing in its total capacities. Detailed characteristics of accidents of certain facilities or equipment in oil depots like storage tanks (Chang & Lin, 2006; Zheng & Chen, 2011; Busciglio et al., 2015), pipelines (Shahriar et al., 2012; Adebayo & Dada, 2008), or any other certain accidents like lightning triggered (Renni et al., 2010) were previously analyzed. However, the overall analysis of fire and explosion accidents in oil depots has not been carried out. In addition, the past fire and explosion accidents of oil depots in China were caused by the similar reasons repeatedly, of which a large number would be prevented by scientific studies or reasonable guidance. The purpose of this paper is to utilize the past statistics of fire and explosion accidents of oil depots in China to identify the most dangerous areas, vulnerable facilities & equipment, ignition sources, types of accident substances, and major causes to propose enough special lessons learned from those accidents to improve the future security management in oil depots.

2. Fire and explosion accidents of oil depots in China

2.1 Overall analysis of accidents

435 cases of fire and explosion accidents of oil depots in China during the period of 1951 to 2013 were collected from papers, books, codes for design and fire protection, reports, and the Internet (Fan et al., 2006;

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China State Construction, 2003 & 2005; Meng et al., 2012; MOHURD, 2009). For the data extraction, selection criteria were defined as follows: (1) the accidents occurred or could have occurred in oil depots in China were related to fire or explosion or fire-to-explosion or secondary explosion or the combination. (2) Some accidents like pipeline rupture or oil spill that had been controlled without a break of fire or explosion were excluded from the data. (3) The fire or explosion accidents occurred or could have occurred in the area of an oil depot, whereas others outside of such area were excluded from the data, and (4) for the reason of not widespread application in the oil depots in China, the accidents of sphere storage tank were not included in the data.

The overview of oil depot accidents in China is shown in Figure 1, and it should be claimed that not all fire and explosion accidents of oil depots in China are collected in Figure 1 for the reason of some unrecorded ones or those which were not showed in printed or electronic form. The reports of these accidents included personnel casualties, poison pollution and economic losses. Because the time span of these accidents is very long, the figures of economic losses are meaningless. Therefore, only the numbers of casualties are collected. The numbers of casualties are listed in Table 1. It can be seen from Figure 1 that the majority of accidents happened during the 1970s and 1980s (174 cases, 40 % and 128 cases, 29.43 %) for the booming of petroleum industry and rapid growth of oil consumption in China. After the Second World War, the total industrialized level of China was poor in the 1950s and 1960s. Thus the number of oil depots was limited, and consequently, the fire and explosion accidents in these two periods, which only account for 2.53 % and 5.52 %, were relatively less than those in any other time scales. By the introduction of scientific security management and awareness of fire protection, the number of accidents during the 1990s decreased enormously from its previous value (about 30 %) to 7.36 %. However, the accident number grew up to 15.17 % in the past decade. Since the rapid increasing of fuel consumption in China, the capacities of oil depots were required to be enlarged. The novel bulk or ultra-large storage tanks were built in some reservoir bases for national strategic reserve, and the application of such newly technology or equipment brought back to high risk of fire and explosion. Besides, most of the oil depots were built in the 1970s or 1980s, so a large number of basic facilities and equipment (such as storage tanks, pipeline system, pumping station, etc) were vulnerable to fire and explosion accidents after 30 or 40 years of service. For this reason, it is sure that the fire and explosion accidents will increase to some extent in the next few years. Table 1 shows the total death and injured numbers of personnel, in which we can find that nearly half of the personnel casualties (42.16 %) were dead or seriously injured. Among all these 435 fire and explosion accidents in oil depots, an average of approximately 3 personnel casualties is listed in every accident, thus it is sure that fire and explosion are extremely harmful for human beings in oil depots.

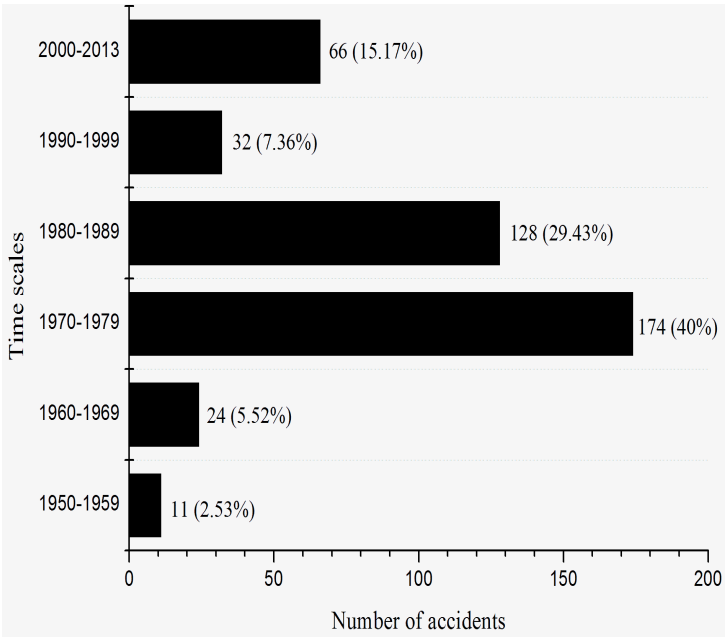

Figure 1: Fire and explosion accidents in oil depot in different time scales

Table 1: Number of casualties

Personnel casualties	Number	Proportion (%)
Death	390	29.10
Seriously injured	175	13.06
Slightly injured	775	57.84
Total	1340	100

2.2 Area of accidents

In terms of the places of oil depot in which fire and explosion accidents broke out, 435 accidents are categorized into four areas, namely the oil storage area (including storage tank farm, fire dike, distribution substation, etc), the loading and unloading operation area (including railway trestle, railroad platform, pumping station, oil dock, oil drum warehouse, oil filling and off-loading equipment, etc), the auxiliary operation area (including firefighting pump station, instruments warehouse, boiler room, laboratory, sewerage, etc), and finally, other areas (including office building, dining hall, dormitory or lounge). The numbers of accidents in different areas and their proportions are shown in Table 2.

Table 2: Area of accidents

Area of Accidents	Number of Accidents	Proportion (%)
Oil storage area	103	23.68
Loading and unloading operation area	222	51.03
Auxiliary operation area	37	8.51
Others	73	16.78
Subtotal	435	100

From Table 2 we can see that over half of the accidents (51.03 %) take place in the loading and unloading operation area. A large amount of fuel-air mixture evaporates from the loading and unloading operation area during the ritual oil filling or off-loading works from oil tank trucks. When encountering the ignition source, such evaporation will lead to severe vapor gas explosion. So the possibility of explosion accidents in such area is bigger than that in any other places. The second most dangerous area is the oil storage area of which the proportion reaches 23.68 %. Storage tanks are the major equipment to store the flammable fuel in oil depots. When the fuel in the storage tanks is ignited by lightning, electric spark or static electricity, it will cause some serious pool fire, surface burning or deflagration within the protective fire dike. Therefore, the possibility of fire accidents in the oil storage area is larger than that in others. However, accidents are not likely to take place in the auxiliary operation area with only 37 cases (8.51 %). But once the fire or explosion breaks out in the auxiliary operation area, such accident may threaten many facilities and equipment in those areas next to it. Additionally, operations in other places of oil depot must be ceased or interrupted by such burning or heating threat. Therefore, the daily security management and safety checkout should be focused on the accident-likely areas like the loading and unloading operation, the oil storage area as well.

2.3 Facilities & equipment of accidents

In view of facilities & equipment in oil depots where fire and explosion accidents happened, 435 cases were taken place in storage tank, oil tank truck, oil pump, oil pipelines, oil drum, and others (including electrical equipment and circuits, wires and cables, engine, measuring instruments, intelligent facilities, etc). Then the statistic data are categorized into these above six groups to find out the relationship between fire and explosion accidents and facilities & equipment. The numbers of different facilities & equipment of accidents and their proportions are shown in Table 3.

Table 3: Facilities & equipment of accidents

Facilities & Equipment	Number of Accidents	Proportion (%)
Storage tank	112	25.75
Oil tank truck	87	20
Oil pump	54	12.41
Oil pipelines	38	8.74
Oil drum	24	5.52
Others	120	27.59
Subtotal	435	100

It is clear in Table 3 that the most vulnerable equipment to fire and explosion is storage tank (112 cases, 25.75 %) regardless of the summation of other types of facilities & equipment which is the largest number of 120 cases (27.59 %). Due to some studies on all kinds of storage tank accidents (Chang & Lin, 2006; Zheng & Chen, 2011), the most triggering reason is lightning, which is in line with the accident statistics of oil storage tanks. In other cases, though, the causes of oil storage tank accidents involve human errors, equipment failure, sabotage, tank crack and rupture, intentional act and nature disaster. The second most vulnerable equipment is the oil tank truck of which the number is 87 (20 %), thus explosion accidents are prone to be brought about during the oil filling or off-loading. This conclusion meets with the above analysis of the area of accidents. Besides, the following high-risk facilities & equipment are oil pump (12.41 %), oil pipelines (8.74 %) and oil drum (5.52 %). Therefore, the storage tanks in the oil storage area and oil tank trucks in the loading and unloading operation area are more important to be taken good care of in the daily security management, and a lot of concentration should also be focused on other high-risk ones such as oil pump, oil pipeline system and oil drums.

2.4 Ignition source and accident substances

Many sources can cause the ignition of fuel-air mixture or stored fuel in an oil depot. From the collection of various causes of 435 fire and explosion accidents, the ignition sources could be divided into 8 groups, namely electric spark, static electricity, lightning, open fire, smoking, heat source (such as engine hot surfaces or heat generated by electric equipment), welding, and other types of sources such as impingement or friction. The ignition sources of these 435 accidents are shown in Table 4, while the substances of fire and explosion accidents are shown in Table 5.

Table 4: Ignition source

Ignition Source	Number of Accidents	Proportion (%)
Electric spark	87	20.00
Static electricity	53	12.18
Lighting	18	4.14
Open fire	66	15.17
Smoking	31	7.13
Heat source	53	12.18
Welding	71	16.32
Others	56	12.87
Subtotal	435	100

Table 5: Type of accident substances

Accident Substances	Number of Accidents	Proportion (%)
Fuel-air mixture	331	76.09
Fuel	77	17.7
Unknown	27	6.21
Subtotal	435	100

From Table 4 we can draw the conclusion that the proportions of different ignition sources are quite evenly distributed. The biggest proportion of ignition source is the electric spark which only takes up 20 %, while other proportions involve the static electricity, open fire, heat source, welding, and other types of ignition sources which are quite similar to each other which is ranging from 12.18 % to 16.32 %. Nevertheless, lightning and smoking take up smaller proportions (18 cases, 4.14 % and 31 cases, 7.13 %). The control of ignition sources should be equally concentrated to several impact factors to all types. Table 5 shows the relationship between substances and these fire and explosion accidents. Despite of some unclear cases, the majority of accident substances are fuel-air mixture which accounts for over 76.09% of total cases. As we all know, ignition of fuel-air mixture tends to a vapor cloud explosion, whereas ignition of the stored fuel tends to accidents like pool fire, surface burning or deflagration. As a result, the accidents in oil depot are likely to be the vapor cloud explosion type. However, recent technologic safety treatment for emergency in oil depots is cooling system, firefighting, fire alarming or fire monitoring, which mostly accentuates fire protection but takes little attention to explosion prevention. So it is urgent to build up a fuel-air mixture explosion prevention system in oil depots to provide a scientific guidance for future security management and emergency reaction.

2.5 Responsibility for accidents

According to the cause investigation of accidents, many reasons would result in fire and explosion in oil depots. The responsibilities for all fire and explosion accidents can be divided into 6 categories, namely the management responsibility (including operation error, maintenance error, poor field guidance, poor fire or explosion safeguards, etc), technologic responsibility (including design deficiency, materials deficiency, construction deficiency of facilities & equipment, poor erosion protection, poor lightning grounding, etc), combined responsibility of both management and technology, external responsibility (including illegal constructions, external buildings which violate the fire separation distance, third party damage, etc), sabotage, and natural disaster. The numbers of different types of responsibility and their proportions are shown in Table 6.

Table 6: Responsibility for accidents

Responsibility for accidents	Number of Accidents	Proportion (%)
Management responsibility	238	54.71
Technologic responsibility	80	18.39
Combined responsibility	90	20.69
External responsibility	23	5.29
Sabotage	4	0.92
Natural disaster	—	—
Subtotal	435	100

From Table 6, it is sure that nearly all the accidents (roughly 94 %) are attributed to management or technologic responsibility, or the combination of both. In addition, approximately 54.71 % of the accidents are related to management responsibility of which the proportion takes up the first place, hence it plays a pivotal role to improve the security management in the daily operation works. Accidents due to management responsibility are likely to break out in the daily routine operation, maintenance and repair, whereas accidents resulted from technologic responsibility are likely to happen at the beginning construction or design of an oil depot. As a result, it is sure that the fire and explosion accidents may break out throughout the whole period of oil depot from its design or construction to afterward operation or management. For this reason, it should be paid more attention to the security management throughout the whole period time. Besides, from the comparison analysis of many fire and explosion accidents of different oil depots in China, many cases are related to similar reasons repeatedly. Most of these accidents could have been prevented or avoided with improvement in security management from scientific guidance.

3. Special lessons learned from the accidents

From those fire and explosion accidents mentioned above, several special lessons learned should be proposed to improve the total safety level of the petroleum storage industry. (1) The major accident substances are fuel-air mixture according to the data statistics. However, the recent firefighting system in an oil depot is based on fire distinguishing not on explosion protection. The basic firefighting equipment includes fire alarm system, fire monitoring system, fire hydrant, etc. which could not effectively deal with an explosion like fuel-air mixture gaseous vapor cloud explosion. The basic scientific explosion protection system like water mist, inert gas or dry powder should be introduced to the oil depot in addition to the original fire extinguishing system. (2) The fire and explosion evaluation system should be changed from the former experience based methods to other more scientific ones by using Fault Tree, Event Tree, System Theory or the Grey System Theory to improve the hierarchy and accuracy of the assessment. (3) The recent lightning protection of the ultra large storage tank is using its metal tank wall to grounding. However, several large fire accidents happened due to the bad electrical connection between the storage tank roof and tank wall. Thus it is strongly recommended that the lightning protection of should be improved by using a separate lightning rod near the storage tank to attract the lightning instead of using its metal tank wall to grounding. (4) The fire and explosion accidents are likely to break out when a large number of basic facilities and equipment in the oil depot are vulnerable to fire and explosion sources after 30 or 40 years of service. Those oil depot built between 1980s and 1990s are at a high risk of fire and explosion accidents, therefore the management responsibility of the personnel in oil depot should be enhanced and the daily security check and safety maintenance should be improved in the next few years.

4. Conclusions

Data and accidents of fire and explosion in oil depot are collected and analyzed. The results provide useful information on most dangerous area and vulnerable facilities & equipment to fire and explosion, i.e. the loading and unloading operation area and the storage tanks. Moreover, various ignition sources are studied to find out that all of them may be possible for a fire and explosion accident in oil depot because of their evenly distributed proportions. The fuel-air mixture is the largest proportion in the accident substances, thus the vapor cloud explosion should be paid more attention to and the explosion prevention would be the major concerns for safety emergency reaction in oil depots. The analysis of responsibility for accidents shows that the management responsibility dominates among all the causes, so it is essential to prevent accidents in the daily routine operation, and security management should be concentrated throughout the whole period time in oil depots. In addition, the majority of fire and explosion accidents of oil depot in China would have been prevented or avoided if the security management had been improved by scientific guidance.

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