Investigation and Analysis of a Hazardous Chemical Accident in the Process Industry: Triggers, Roots, and Lessons Learned

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This paper performs an in-depth investigation and analysis on a catastrophic hazardous chemical accident involving domino effects in China based on an emerging accident causation model—the 24Model. The triggers and roots of the incident from the individual and organizational levels have been identified and several useful lessons have been summarized to avoid similar mistakes. This accident began with a leak of vinyl chloride caused by the failure of the gas holder's bell housing and the operators' mishandling. Leaked vinyl chloride was ignited by a high-temperature device in the process of diffusion and the fire quickly spread to the illegally parked vehicles. Several organizations were involved in this accident, and the chemical company should bear the main responsibility for it, and shall establish and implement an effective safety management system in its organizational structure and staffing, facilities management, hazards identification, emergency disposal, etc., to improve safety performance in a systematic way. Enterprises in the chemical industry park shall enhance the communication to clarify major hazard installations in their domains, and conduct regular safety evaluation for the plant as the external environment changed. Government agencies shall plan the layout of the chemical industry park scientifically and ensure safety starts with the design stage. The case study provides a practical procedure for accident investigation and analysis, and thus, preventive measures can be made according to the various causations at different levels.

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Case Report

Investigation and Analysis of a Hazardous Chemical Accident in the Process Industry: Triggers, Roots, and Lessons Learned

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Keywords: hazardous chemical accident; cause analysis; 24Model; individual; organization

1. Introduction

1.1. Background of the Accident

Hazardous chemicals have the characteristics of inflammability, explosiveness, toxicity, and corrosiveness. When accidental events occur in the chemicals' production, storage, transportation, or other processes, they often lead to multiple domino effects and may spawn serious consequences of mass casualties, property losses, and environmental pollution [1]. This kind of disaster is very important in process safety and risk management [2], and it occurs in China's process industry very frequently, and even shows an increasing trend year-by-year [3]. In the last few years, different measures in aspects of the integration of chemical industrial parks, the monitor and control of operator behaviors, the revision of related laws and regulations, etc., have been taken by the Chinese government to improve the situation, and people carried out extensive research on the occurrence of hazardous chemical accidents [4–6]. However, the effect is not as expected. According to the statistics, there were at least 1653 hazardous chemical accidents and 500 deaths in this country in 2019 [7], and the leak and explosion of hazardous chemicals in the production and storage which were more likely to lead to severe consequences occurred almost every year (see Table 1). It seems that the research on the analysis and prevention of particularly major hazardous chemical accidents still has a long way to go in the industry or even the country. For every accident, to find out the various causes is of vital importance and, thus, targeted preventive measures can be made to avoid similar mistakes. The process of occurrence and development of these accidents is often very complex and involves many different causal factors, so great efforts should be taken to help individuals and organizations better remember the cases and useful lessons.

Table 1. Some of the serious hazardous chemical accidents in China.

Year	City Where Accidents Occurred	Accident Classification	Process	Deaths	Injuries
2013	Qingdao, Shandong	Leak and explosion of the crude oil	Transport	62	136
2014	Suzhou, Jiangsu	Explosion of aluminum-alloy dust	Production	97	163
2015	Tianjin Port	Spontaneous combustion of nitrocellulose and explosion of ammonium nitrate	Storage	173	798
2015	Dongying, Shandong	Explosion of mixed dinitrobenzene process unit	Production	13	25
2017	Lianyungang, Jiangsu	Leak and explosion of M-dichlorobenzene process unit	Production	10	1
2017	Linyi, Shandong	Leak and explosion of the liquefied petroleum gas tanker	Loading and unloading	10	9
2018	Yibin, Hubei	Explosion of butylamide, sodium chlorate, methylbenzene, etc.	Production	19	12
2018	Zhangjiakou, Hebei	Leak and explosion of chloroethylene	Production	24	21
2019	Sanmenxia, Henan	Leak of liquid oxygen and explosion of combustible materials	Production	15	16
2019	Yancheng, Jiangsu	Spontaneous combustion and explosion of nitrification wastes	Storage	78	716

The best approach to learning about safety is to draw lessons from accidents [8]: it is a great challenge to remember key safety cases so as to avoid the deficiencies from the individual behaviors and organizational management in practice since there are endless accident cases, and accompanying causes, throughout the world [9,10]. The case selected to be discussed in the present paper is just the Zhangjiakou leak and explosion accident in Table 1, which is one of the most severe accident in recent years and is the latest to be investigated and published an official report. This disastrous hazardous chemical accident occurred in Hebei Shenghua Chemical Company (hereinafter, Shenghua Company, Zhangjiakou, China) on 28 November, 2018, and it caused 24 deaths, 21 injuries, more than 50 vehicles damage, and lots of building fires due to the domino effect [11]. It brought a huge negative social impact in the country and caused widespread concerns in the process industry. The public could not understand why the impact scope of the explosion was so extensive and wanted to find out how the accident was triggered—as well as what causes the mass casualties and losses all the time. This accident, once again, stresses the importance of acknowledging the hazards of the process industry as well as the need for continually updating the knowledge and awareness required for preventing such catastrophes in the future [12,13].

1.2. Theoretical Basis for Accident Analysis

Accident analysis/investigation is widely recognized as an important part of a comprehensive and efficient process safety management (PSM) [10]. The Ministry of Emergency Management of the People's Republic of China (PRC) has already finished and published an accident investigation report. The report detailed multiple causal factors by conditions, individuals, and organizations, the combination of which led to the system failure [11], which also provides first-hand information for accident analysis and prevention. The key point on how to avoid similar mistakes should be remembered, and it is vitally important everywhere within the industry. Therefore, this study intends to perform an in-depth analysis for the process of the accident, and to identify, classify, and present all causes based on available data. Thus, useful experiences and lessons could be summarized and learned to provide guidance for the safety management of various enterprises and the safety supervision of government agencies. In this regard, graphic presentation techniques, such as the accident causation model, event sequence diagram (ESD), and Fishbone diagram have been utilized. Particularly, the accident causation model plays an important role in this work because it demonstrates the logical relationships among different causal factors and can help people better understand and remember the key lessons [9]. Therefore, how to select an effective accident causation model is of vital importance for the accident analysis.

Indeed, numerous accident causation models were proposed and used in the domain of safety research in the past decades. Currently, several typical ones dominate the literature: accident-proneness model [14]; domino-accident causation model [15]; the loss causation model [16]; the risk management framework (i.e., the AcciMap) [17]; the Swiss Cheese Model (SCM) [18]; Human Factors Analysis and Classification System (HFACS) [19,20]; Systems Theoretic Accident Model and Process (STAMP) [21,22], etc. Each accident causation model engenders its own distinct approach when used for analyzing accidents. For example, the HFACS inspired by the SCM was initially applied for the taxonomy of human errors in aviation accidents, and in recent years, it involved other domains, such as coal mining safety [23] and maritime safety [24].

Our research team has always focused on how accidents unfold, and carried out extensive research on those accident causation models. Through in-depth comparison, the common disadvantage lies in that they fail to well define the accident causation, and each level, so that people may not prevent accidents by directly, accurately, or conveniently applying the analytical processes and interpreting their results [6]. Thus, the members have summarized the advantages and disadvantages of many typical models and attempted to propose an improved one, which was named the 24Model [9]. The model determines the taxonomies and specific contents of various accident causes and further optimizes their logical relationships and theoretical framework. Indeed, the 24Model has already been applied to several high-risk domains for accident analysis and prevention, from coalmine [25,26] to construction [27], to aviation [28], to shipping [29], etc., and we believe it can also improve the safety and sustainability in the process industry. Thus, another important aim of this article is to verify the availability of this model in the process safety field through the typical case, and to try to promote a universal method to analyze or investigate accidents for researchers, practitioners, and investigators. We have to admit, however, that the 24model may not be perfect, and needs to be continuously refined through a large number of case studies.

2. Method

In this study, the 24Model mentioned above is chosen as the tool for the analysis of this hazardous chemical accident, and its specific framework is shown in Figure 1. Here, "2" means causes at the individual level and organizational level; "4" means the causes classification, including unsafe acts and unsafe conditions, flaws in habitual behaviors, deficiencies in safety management system, weaknesses in safety culture [30,31]. The 24Model indicates that all accidents belong to the organization and are mainly attributed to internal organizational causes (at both individual and organizational levels) [32,33]. The internal causes are much more changeable and controllable for the managers of the organization to achieve improvement in safety performance, so they usually serve as the key points for accident investigation and analysis. The external causes mainly involve factors from natural events, defective design, poor supervision from the government, deficiencies in laws or regulations, etc. [3,6], which generally contribute to accidents by influencing the internal ones.

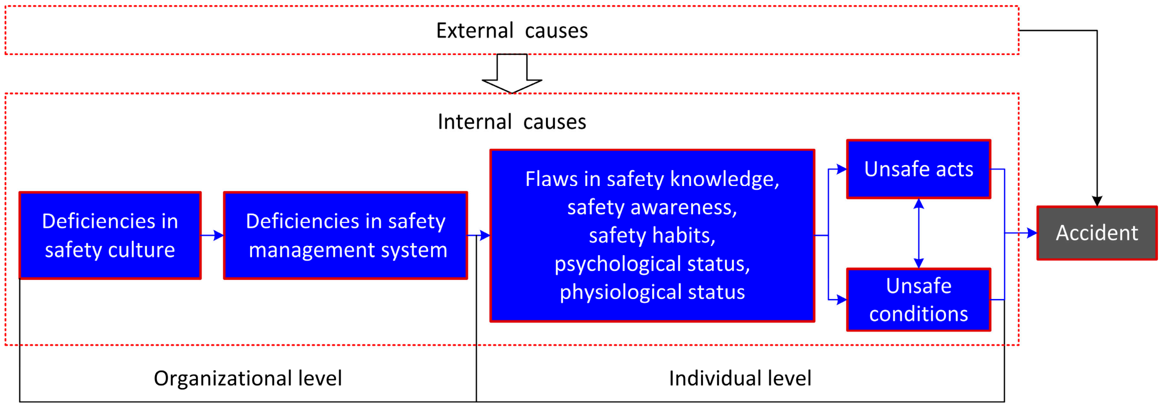

Figure 1. The framework of 24Model [25–27].

Heinrich proposed that unsafe acts and unsafe conditions are the immediate causes of an accident [15]; moreover, they were determined by various factors, such as individual safety knowledge, safety awareness, safety habits [32], as well as their psychological and physiological status [25]. It is recognized that errors from the individual level are caused by root causes, i.e., the weaknesses in organizational safety management and safety culture [19,34]. The safety management in an organization is carried out via a safety management system; therefore, the deficiencies in the safety management system, in turn, can be used as indicators to demonstrate the flaws in safety management. The elements of the management system have been introduced in occupational health and safety (OH&S) management systems [35], mainly involving safety objectives, organizational structure and safety accountabilities, management commitment, hazard identification, training and education, resource management, safety communication, emergency response planning, etc. Safety culture, which reflects beliefs, values, and attitudes shared by the staff related to safety, guides the making and implementation of the safety management system [25]; thus, poor safety culture or climate in an organization will definitely lead to the deficient safety management system. Safety culture consists of many key elements affecting the safety performance [36,37], mainly including the importance of safety, economic benefits of safety, role of safety awareness, demand of safety training, primary responsibility for safety, safety responsibility of managers, role of safety regulations, etc. [6,33].

For ease of application of the 24Model in accident analysis, a standard procedure has been given in this study. A specific flow chart has been drawn and shown in Figure 2. The downward arrows mean the main step for accident analysis, which begins from the bad outcomes (i.e., accident case) to the identification of critical events and organizations, to the analysis of internal causes and external causes, and finally, to the visualization of the analysis results. The consensus process for the analysis of an accident is summarized as follows:

- performing the events segmentation for accidents, especially for those involving domino effects, and identifying the critical events related to the occurrence and development of the accident based on the process or timeline;
- identifying all organizations (e.g., the design institute, the interested parties, the regulators, etc.) related to the accident and finding out the one in which the accident occurred;
- identifying all unsafe acts and unsafe conditions leading to the critical events by consulting related laws or regulations, and classifying them according to the violations, staff, materials, facilities, places, etc.;

- determining the specific flaws in individual safety knowledge, safety awareness, safety habits, psychological status and psychological status according to the unsafe acts or unsafe conditions;
- mining or deducing the deficiencies in the development and implementation of organizational safety management system based on the framework in the OH&S management system.
- mining or deducing the weaknesses in the construction of organizational safety culture carriers (i.e., the medium or tool to display and spread the safety concept) and member understanding for safety culture elements;
- performing the analysis of other causal factors from external organizations according to the above steps;
- achieving the visualization of all causal factors based on the 24Model.

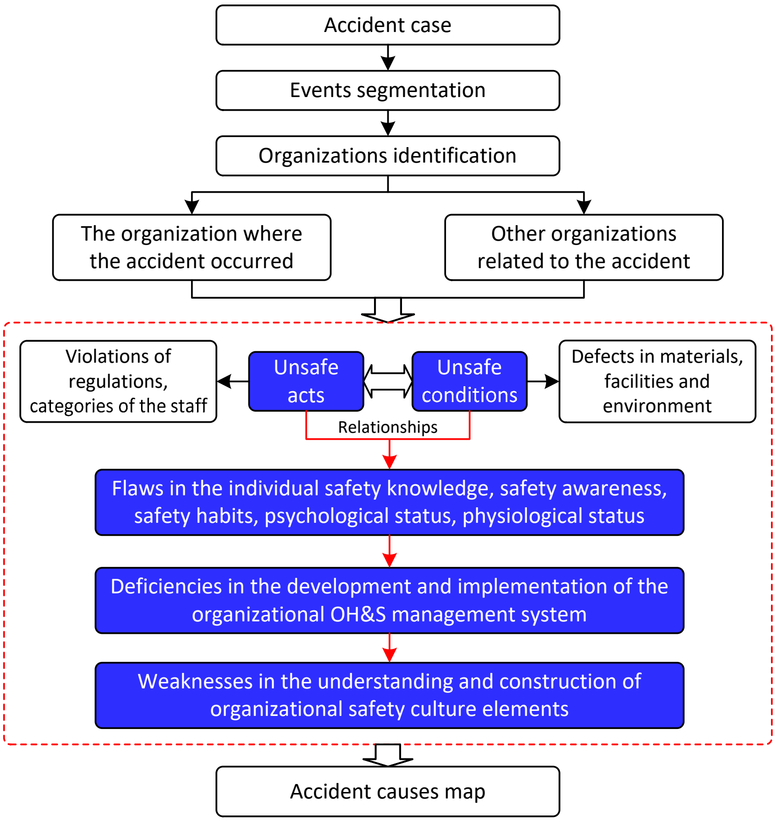

Figure 2. The accident analysis procedure.

3. Accident Overview

3.1. Substance and Installation

This accident began with a leak of vinyl chloride stored in Shenghua Company; the leaked gas was ignited by a high-temperature device in the process of diffusion, and subsequently, the initial ignition further transitioned to a devastating detonation. Shenghua Company mainly produces polyvinyl chloride resin and caustic soda. Therefore, vinyl chloride, as an important intermediate product, usually needs to be used or stored in large quantities in the plant, and the accident just happened in the process of its compression and condensation. The brief process flow diagram about vinyl chloride is shown in Figure 3. In China, vinyl chloride is a flammable, explosive, and toxic chemical listed in the Hazardous Chemicals Catalogue. It has a low flash point (−78 °C) and a wide range of explosive limits (from 3.6% to 33% by volume), and the mixture with air is easily ignited once meeting the open fire or hot surface. This shows that vinyl chloride is extremely flammable and dangerous, so close attention should be paid in the process of the production, storage, as well as use of this substance.

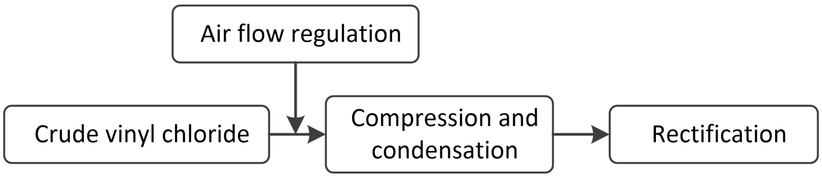

Figure 3. The process flow diagram related to this incident.

Through on-site investigations, the storage installations of vinyl chloride are located on the south side of Shenghua Company. There are three gas holders distributed from west to east, with volumes of 5300 m^3 (1#), 2500 m^3 (2#), and 2500 m^3 (3#), as well as two similar spherical tanks installed side-by-side, with a volume of 2000 m^3. The specific distribution in the plant is shown in Figure 4 below. According to the accident report, the leaks just occurred in the 1# gas holder with the largest amount of vinyl chloride. This installation is designed as a double-layer bell-shaped structure sealed by the water. When the bell housing pulls the middle section up, a U-shaped annular water seal will be formed. The designed height of the water seal is about 0.350 m, which can seal vinyl chloride of 3.43 kPa. The schematic structure of 1# vinyl chloride gas holder is shown in Figure 5.

Figure 4. The map of the accident scene.

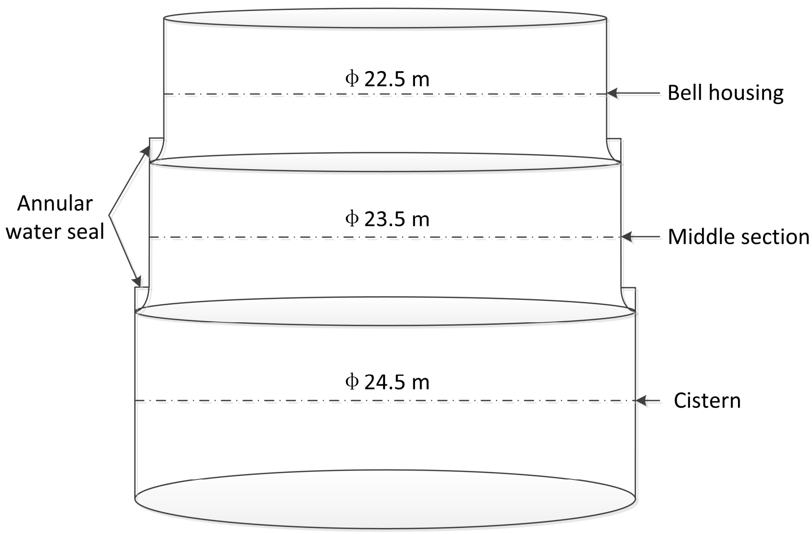

Figure 5. The structure diagram of 1# vinyl chloride gas holder.

Additionally, in order to realize the real-time monitoring for the leak of vinyl chloride, both the 1# and 2# gas holders had been equipped with gas detection system by the company; however, the devices were in a failure state and did not send any alarm signals when the leak occurred.

3.2. Process and Consequence

At 0:36:53 a.m. on 28 November, 2018, the operational data in the Distributed Control System (DCS) of Shenghua Company's polyvinyl chloride (PVC) workshop showed that the inlet pressure of the compressor connected with 1# chloroethylene gas holder suddenly dropped from 0.19 kPa to 0.05 kPa. The DCS operators discovered this change but mistakenly thought that there was just a normal shortage of raw materials in the installation. Therefore, they began to manually adjust the return valve of the compressor to reduce the amount of vinyl chloride flowing into the rectifying tower to maintain the stability of the whole pressure system. The opening degree of the return valve increased from 30% to 60%, and finally to 80% in about 3 min, and a lot of gases returned to the gas holder. The change of the inlet pressure of the compressor in the process of dynamic adjustment of the return valve is shown in Figure 6 below. Obviously, the final inlet pressure of the compressor was still only 0.13 kPa, without returning to the normal level. This supports that vinyl chloride might leak from the gas holder.

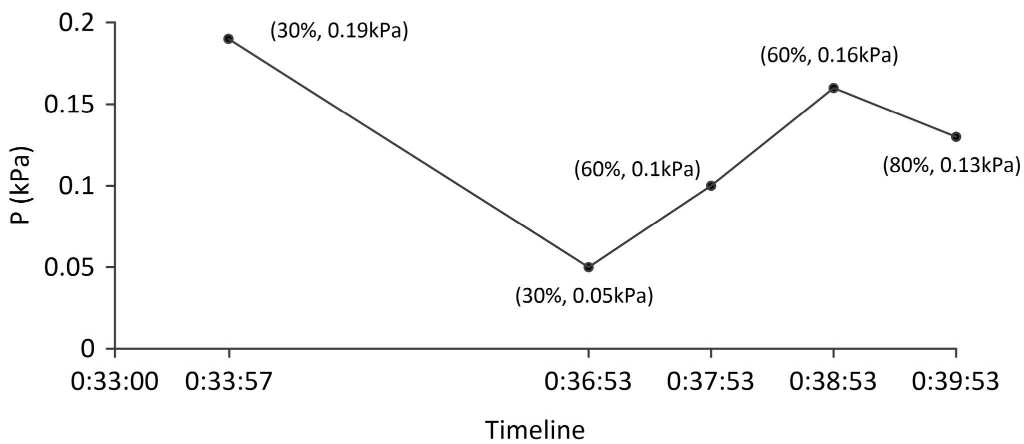

Figure 6. Changes of the inlet pressure of the compressor under different opening degrees of the return valve.

At the same time, the DCS data indicated that the height of 1# gas holder dropped rapidly during the process of opening the return valve. The height gauge on both sides (the west side and east side based on Figure 4 above) of 1# gas holder recorded the changes, which can be seen in Figure 7 below. This further confirmed that a large amount of leaks of vinyl chloride occurred in this gas holder. Through the review of on-site surveillance videos, the fire first appeared on the south of the gas holder outside the factory at 0:40:55 a.m., and just a few seconds later, the staff on duty heard the explosion one after another.

As shown in Figure 3, the vinyl chloride gas holder group is located at the southernmost side of Shenghua Company, about 20 m away from the north side of the Provincial Highway 310. Affected by the local terrain condition and the wind direction at the time of the accident, the leaked vinyl chloride spread along the road extensively and diffused to the opposite Haipoer New Energy Technology Company (hereinafter, Haipoer Company, Zhangjiakou, China) who was mainly engaged in the preparation of hydrogen and oxygen by electrolysis of water. Through the on-site surveillance videos, eyewitness interviews and fire spread path analyses, the investigators finally determined that the fire source resulting in the explosion was from a high-temperature muffle furnace near the oxygen preparation and filling area in Haipoer Company. A further investigation and test showed the device had been continuously energized for 4 h and 24 min by the time of the incident, and the temperature at the hole in the back wall of the furnace was up to 1000 °C, far exceeding the ignition temperature of vinyl chloride (472 °C) [38].

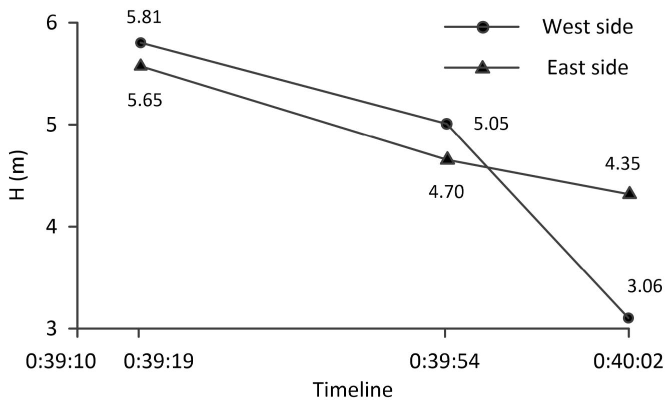

Figure 7. Changes of the height of 1# gas holder after vinyl chloride leaked.

When the explosion occurred, lots of vehicles loaded with raw materials and fuels (coal) hired by Shenghua Company, as well as several small passenger cars were being illegally parked on the Provincial Highway 310 and the opposite illegal parking lot. Many drivers and supercargoes stayed in the trucks overnight because of Shenghua Company's delay of unloading. After the leaked vinyl chloride was ignited, the fire rapidly spread to the vehicles; moreover, the fire further expanded and quickly formed domino effects (see Figure 8) due to the flammable and explosive substances in the vehicles. Therefore, it was not surprising that the accident caused such heavy casualties and property losses.

Figure 8. Damaged vehicles on the Provincial Highway 310.

4. Accident Anatomy

4.1. Sequential Events

This hazardous chemical accident once again indicated that even a minor change in process can have vast consequences [39]. Typically, large-scale accidents occur because of unexpected interactions among multiple failures and one component's failure triggers failures in other components or subsystems [40,41]. This incident began with a change of pressure system caused by a local leak of a vinyl chloride gas holder, but it eventually evolved into multiple fires and explosions. Based on this, we performed a detailed anatomy on the occurrence and development of this accident, and several critical events were identified from the investigation report. For the sake of better illustration, an ESD has been further developed which can be seen in Figure 9.

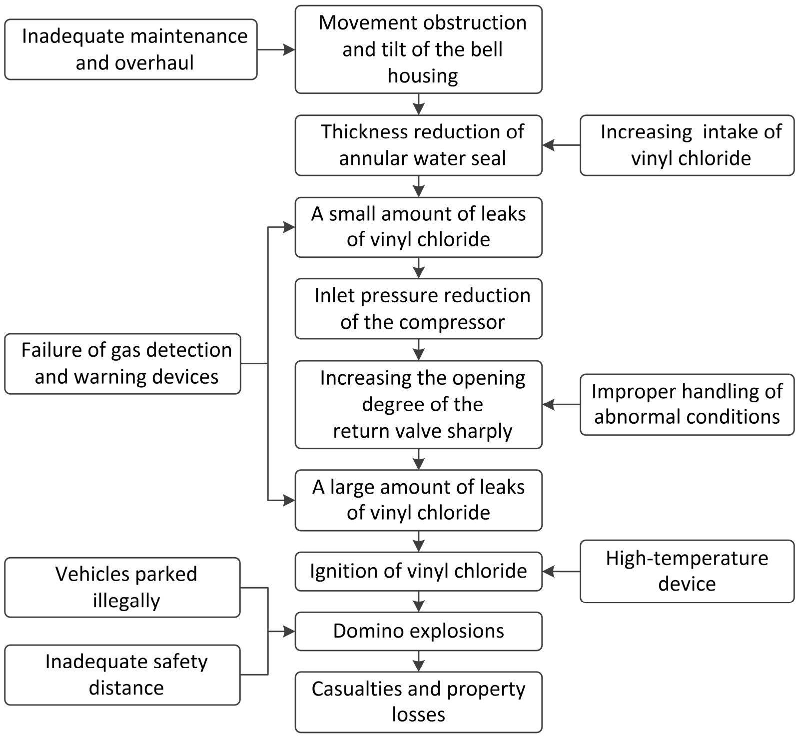

Figure 9. Event sequence diagram (ESD) of the accident.

As shown in Figure 5 above, 1# vinyl chloride gas holder consists of three main parts: the bell housing, the middle section, and the cistern. The bell housing and the middle section are connected with several pairs of matched guide rails and guide rollers, and the bell housing can move up and down with the change of the pressure (i.e., the content of vinyl chloride) in the gas holder. However, before the accident, the DCS data showed the height of 1# gas holder did not change with the increase of vinyl chloride for a long time, so it can be supposed that there was a movement obstruction between the bell housing and the middle section. Through on-site investigations for this gas holder, it was found that a large gap was formed between a pair of guide roller and guide rail on one side of the bell housing, and meanwhile, there was a deep sliding friction trace on the symmetrical side, thus leaving the bell housing in a tilt and stagnation condition.

Due to the tilt of the bell housing, the height of the annular water seal on one side of the gas holder is bound to decrease, and the specific thickness reduction h is as shown in Figure 10. According to the similar triangle principle:

$$h/22.5 = a/6.5$$

where a means the maximum gap between the guide rail and guide roller, and is 0.043 m wide through field measurement. By further calculations, the thickness reduction (h) of annular water seal is 0.149 m, so the minimum height of the water seal is 0.201 m (0.35 minus 0.149). This height can only seal the air pressure of 1.9 kPa at the maximum. In this case, the water seal of the gas holder was almost in a failure state.

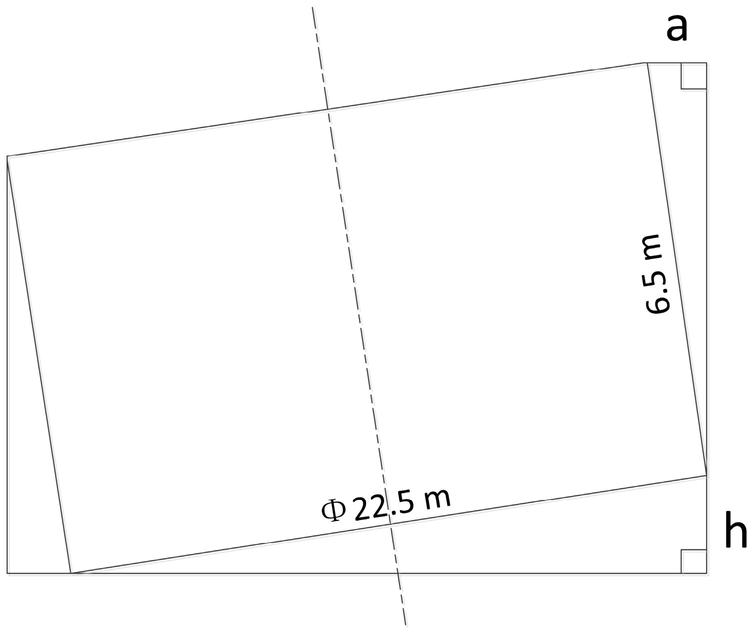

Figure 10. The schematic diagram of the tilting state of the bell housing.

The internal pressure of the gas holder increased with the increasing intake of vinyl chloride gradually, and the gas broke through the water seal eventually. After the initial leaks of the vessel, the pressure at the inlet of the compressor decreased quickly, but the operators were not aware of the breakdown of the gas holder. While in the absence of safety check and report, they quickly increased the opening degree of the return valve of the compressor according to the normal operation mode to supplement the pressure inside the gas holder; thus, further resulting in continuous leaks of vinyl chloride. The real height of vinyl chloride gas holder is 5.9 m, and through field survey, the height of the gas holder decreased to about 0.9 m after the accident. The diameter of the bell housing is 22.5 m, and the leakage volume of vinyl chloride is estimated as:

$$\Pi R^2 \times H = 3.14 \times (22.5 \div 2)^2 \times 5 \approx 2046 \text{ m}^3$$

As mentioned above, though Shenghua Company had installed gas detection devices around the 1# vinyl chloride gas holder, the devices were being in a failure state due to the improper use and management in the production and did not send any alarm signals when the leak occurred, which made the on-duty personnel fail to find the danger in time.

4.2. Involved Organizations

In the complex sociotechnical system, accidents usually occur in an organization and are affected by other factors outside the organization [18]. The interactions between different organizations should be considered in a comprehensive manner when carrying out the analysis and prevention of accidents. Similarly, several organizations were involved in this hazardous chemical accident, among of which, Shenghua Company was just the organization where the accident occurred, and the causes associated with it are the emphasis for investigation and analysis. Besides, other related organizations, such as the supplier transportation company, the illegal parking lot, the Haipoer Company, and some relevant government agencies (i.e., the local traffic control department, the local land and resources department, as well as the local supervision department of work safety), exerted indirect effects on the occurrence of the accident and the expansion of various losses. Therefore, the adverse factors from those interested parties should also be taken seriously. The interrelationship among these organizations in the accident are shown in Figure 11.

Figure 11. Organizations involved in the accident and the interrelationship among them.

Safety inspections from related government agencies were far from enough in this accident. The local traffic control department failed to perform its duties well: the traffic order in front of Shenghua Company's gate on the Provincial Highway 310 was chaotic all the time and the existing no-parking signs set on this section were actually ineffective. The long-term parking illegally was not resolved by this department in a timely and effective manner, which was one of the main reasons for the heavy casualties and damaged vehicles in the accident. As we all know, the local land and resources department plays an important role in the planning and design of a chemical industry park and shall, in accordance with related regulations or standards, carry out a strict examination and approval for the utilization and layout of the land. However, the safety distance between Shenghua Company and the highway, as well as its surrounding enterprises was far from meeting the requirement of engineering standards. Once there is an accident, it will inevitably lead to domino effects. By law, the local safety supervision department must be equipped with sufficient professionals to conduct regular safety inspections for enterprises in the chemical industry park, particularly to strengthen the supervision for the identification and assessment of major hazard installations in chemical production enterprises. If there is any risk, the supervision department must enforce and guide the enterprise to formulate and implement corrective measures promptly, and achieve the closed-loop management of safety inspection through the form of "reviewing".

Shenghua Company, as the organization where the accident occurred, failed to cooperate with the local supervision department to carry out the daily safety inspection and hazards rectification, and neglected the communication with the suppliers, project contractors, as well as other related parties. As a member in the chemical industry park, Shenghua Company has the responsibility to assist the local traffic control department to direct and divert the outside vehicles, and should strictly control the number and time of the vehicles parked inside and outside its plant. According to requirements in the Production Safety Law of the People's Republic of China (PRC), production and business units shall be responsible for the safety supervision of the interested parties who worked within their jurisdiction. Thus, Shenghua Company shall assist the suppliers (i.e., the transportation company) in the employee supervision, facility management, hazard identification, safety training, emergency disposal, etc.; moreover, it is better to communicate with the suppliers about the business in advance to improve the unloading efficiency, thereby reducing the vehicle parking time in the chemical industry park. Moreover, Shenghua Company should proactively communicate with the surrounding organizations, and announce all major hazard installations existing in its plant in a timely and feasible manner. Based on the characteristics of the identified hazards and their risk assessment results, Shenghua Company could further remind relevant enterprises to improve their safety management, and develop targeted emergency response plans with them and conduct the regular emergency drill jointly.

5. Causation Analysis and Discussion

Typically, large-scale accidents occur because of unexpected interactions among multiple failures. Based on the above analysis about sequential events and involved organizations, there was a nested collection of roots and causes that led to this accident. These causes ranged from straightforward ones (e.g., mechanical defects) to more fundamental roots, such as managerial flaws or poor safety culture in the organization. In order to illustrate the role played by all casual factors, a Fishbone diagram has been developed for the accident. The Fishbone diagram (also called Ishikawa diagram or cause and effect diagram) was invented by Ishikawa and Luo and it is used to summarize the causes that create or contribute to a specific effect [42,43]. The Fishbone diagram indicates the relationship between a problem and its underlying causes, which is a qualitative analysis tool to identify incident causes [44]. With a step-by-step in-depth study to analyze potential influencing factors, the Fishbone diagram can systematize complicated incident causes. Accordingly, major causes of this accident have been categorized under six topics, as shown in Figure 12.

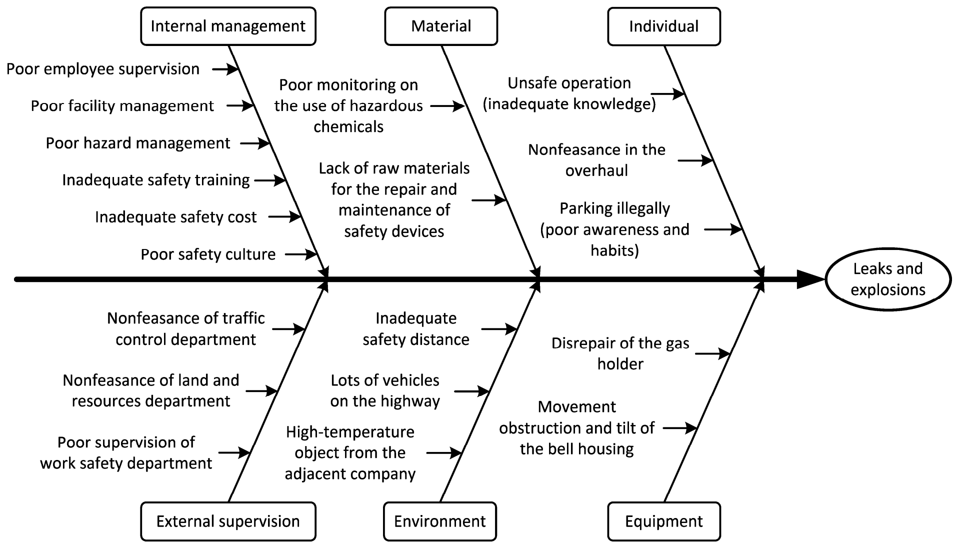

Figure 12. Fishbone diagram of the causes of the hazardous chemical accident.

It can be seen that the number of sub-causes under the individual, environment, internal management, and external supervision categories is more than the other categories, and the further analysis and discussion will be carried out for them in the following section.

5.1. Unsafe Acts at the Individual Level

According to Heinrich's domino accident causation theory, unsafe acts and unsafe conditions are considered as the direct causes of accidents [15]; there is no exception for this accident. Moreover, a large number of statistical analyses of accident causes have shown that most unsafe physical conditions related to accidents, in particular the defects of some facilities, were caused by the operator's unsafe acts [25]; therefore, identifying and eliminating those specific unsafe acts is of crucial importance for the prevention of such accidents. The above accident in Shenghua Company was just classified as an "accountability accident" by the Ministry of Emergency Management of the PRC [11]; that is, scrupulous attention should be paid to human factors when performing cause analysis. Based on this, we identified several key unsafe acts from this accident, as well as gave corresponding unsafe physical conditions or serious consequences caused by them, which can be seen in Table 2.

By consulting related laws or engineering standards, the individual unsafe acts related to this accident were almost all violations. Thus, the direct and effective way to prevent such accidents is to strengthen the safety supervision and behavior controls for individuals in the organization. If the equipment management personnel conduct regular inspections and maintenance on vinyl chloride gas holders strictly according to the organizational regulations in Table 2, the tilt and movement obstruction of the bell housing could be discovered, or even avoided, and the vinyl chloride leaks would not happen. If the gas detection devices on both sides of the gas holder were regulated and opened effectively, the initial leaks of vinyl chloride would be detected and disposed of timely. If the DCS operators were able to identify the abnormal changes of the pressure accurately and take effective response measures, then further leaks and spread of vinyl chloride would not continue. If the truck drivers strictly abide by the prohibition signs set on Provincial Highway 310, the casualties and property losses might not be so severe.

Table 2. Individual's unsafe acts associated with the hazardous chemical accident.

No.	Unsafe Acts	Consequences	Violations of Relevant Laws and Regulations
1	Not having the gas holder overhauled within 6 years.	The bell housing was in a tilted and stagnated state, which was considered a crucial factor causing the leak of vinyl chloride.	In violation of the Regulations for Maintenance and Overhaul of Gas Holders: the period of maintenance and overhaul of gas holders is generally 2–5 years; In violation of the Regulations for Maintenance and Overhaul of Low Pressure Wet-type Gas Holders in Shenghua Company: the medium maintenance period of gas holders is 1–2 years, and the overhaul period is 5–6 years.
2	Adjusting the return valve of the compressor sharply.	The vinyl chloride broke through the annular water seal and leaked in large quantities.	It was a high-risk act that violated the organizational standard operating procedure that stipulates the matters needing attention in the operation of various equipment.
3	Improper use and management of gas detection device (e.g., operating roughly, turning off alarm devices frequently).	The gas detection device malfunctioned and did not alert the operator when vinyl chloride leaked.	In violation of the Interim Regulations on the Supervision of Major Hazard Installations for Dangerous Chemicals: major hazard installations should be equipped with reliable monitoring and alarm devices for the leak of combustible and toxic gases, and those devices should have the functions of information transmission, continuous records, accident alerts, as well as information storage.
4	Parking illegally.	The vehicles were ignited one after another, which expanded the casualties and property losses.	In violation of the safety signs set by the government traffic control department: ten no-parking signs were dispersedly set on Provincial Highway 310 close to the side of Shenghua Company to warn drivers.

Many previous accident investigations have shown that, behind the direct causal factors resulting in the accident, such as unsafe working conditions and unsafe individual acts, there must be deficiencies with respect to the organizational management [18]. That is, the root cause of an accident lies in the errors at the organizational level. Similarly, the above analyses on sequential events and immediate causal factors indicate that the root causes of this hazardous chemical accident involved several elements of organizational process safety management, these being the communication between interested parties, operation procedures, safety design, safety training, risk identification, assessment, etc. They are the roots of the accident, which are usually considered as the key factors in formulating accident prevention countermeasures. The details of these elements will be further discussed below.

5.2. Deficiencies in Organizational Safety Management

Deficiencies in the organization's safety management system are the main reason for individual unsafe acts and some physical unsafe conditions [6]. The safety management system is an important and effective tool for the organizations to ensure their safety performance; therefore, the organizations shall, in accordance with the requirements of laws, regulations, or engineer standards, and their actual production situation, establish a series of sound safety management systems and ensure the members can strictly put them into effect [30,31]. Due to the detailed explanation about the active failures in the official investigation report, unsafe acts and unsafe conditions that caused the accident can be directly acquired, whereas, latent causes related to organizational safety management usually needed to be mined or inferred from the individual's behaviors, or other collected information, as much as possible. In this study, the framework in the OH&S management system and the Production Safety Law of the PRC was used to identify the failures in organizational safety management system elements. In this case, there were many deficiencies in Shenghua Company's safety management system: procedures such as the organizational structure and staff allocation, personnel safety responsibility, safety investment, facility management, hazards identification, emergency management, etc., were not well developed and implemented in its production and operation. All of these deficiencies are summarized in Table 3.

Table 3. Deficiencies in Shenghua Company's safety management system.

No.	Safety Management System Elements	Specific Deficiencies	Stipulations in Relevant Laws and Regulations
1	Organizational structure and staff allocation	1) No specialized safety management department. 2) No specialized equipment management department. 3) Lack of full-time safety management personnel.	Article 21 in the Production Safety Law of the People's Republic of China: the business entity that produces, manages, and stores hazardous substances shall set up a specialized safety management organization or have sufficient full-time safety management personnel.
2	Safety responsibility	1) Poor safety supervision and leadership of the management (i.e., nonfeasance, or absence without leave). 2) No procedures to define and assess the responsibility of the management.	Article 22 in the Production Safety Law of the PRC: both the safety management organization and the safety management personnel of the business entities shall perform their respective accountabilities (total 7 articles).
3	Safety investment	1) Improper use and management for safety costs (i.e., failing to set up special funds for safety purposes). 2) Lack of funds in the purchase of repair materials, as well as the maintenance of safety devices.	Article 20 in the Production Safety Law of the PRC: business entities shall create a special account for safety costs, and invest sufficient capitals for the safe production every year; meanwhile, the management shall extract the funds strictly in accordance with the provisions, and cannot use them for other purposes.
4	Facilities management	1) Poor implementation of the system regarding the equipment maintenance and use (e.g., not having the gas holder overhauled for a long time, non-regular maintenance caused the failure of gas detection devices) due to the absence of feasible process to assess the effect. 2) Rough equipment operating procedures (i.e., lack of detailed procedures and regulatory requirements for the return valve of the compressor).	Regulations for the Maintenance and Overhaul of Low Pressure Wet-type Gas Holders in Shenghua Company: the medium maintenance period of gas holders is 1–2 years, and the overhaul period is 5–6 years. Article 13 in the Interim Provisions on the Supervision of Major Hazard Installations for Dangerous Chemicals: major hazard installations shall be equipped with an uninterrupted collection and monitoring system for the temperature, pressure, liquid level, flow and composition, as well as a gas leak detection and alarm device, with functions of information transmission, continuous record, accidents alert, as well as information storage.
5	Hazard identification	1) No feasible procedure or process to assess the effect of the hazard identification for some key installations and the suppliers' operating areas. 2) Failing to achieve the closed-loop management for hazards (i.e., from identification, to record, to analysis, to assessment, and to elimination).	Article 38 in the Production Safety Law of the PRC: business entities shall establish a perfect hazards identification and elimination system, and take technological and management measures to discover and eliminate the potential hazards that may cause an accident in a timely manner; meanwhile, the detailed information about the hazards should be accurately recorded and promptly informed to the employees.
6	Training and education	1) Lack of training programs on the theoretical knowledge such as the characteristics of some hazardous substances, meaning of some process indicators, etc. 2) Lack of training programs on the practical operation, such as the operation skill or experience, emergency handling capacity, etc.	Article 25 in the Production Safety Law of the PRC: business entities shall provide adequate safety education and training programs to employees to ensure that they master necessary safety theory knowledge and safety operation skills, and are familiar with relevant safety regulations, operating procedures and emergency measures.
7	Emergency disposal	1) Failing to give all possible industrial accident types and corresponding response procedures in the emergency plan. 2) Failing to carry out emergency drills with the staff of suppliers jointly.	Article 12 in the Measures for the Administration of Emergency Plans for Production Safety Accidents: business entities shall, in accordance with the relevant laws, regulations, and standards, as well as in combination with their own safety management system, production scale, and the characteristics of possible accidents, establish a feasible emergency response plan.

The deficient safety management system of Shenghua Company indicated that members in the organization did not reach an agreement on the safety beliefs/values such as "safety is the first priority in production", "the importance of safety management system", "organizational safety performance depends on individual safety awareness", "the importance of safety management for interested parties", etc. The staff ignored that safety should be put in the first place in the daily work and they did not pay enough attention to the roles of safety awareness and responsibility system played for accident prevention. In particular, the management failed to deeply understand the PSM program-its importance for maintaining both safe operations and compliance, key roles and responsibilities, current issues, and challenges the organization faced in its implementation. As we all know, good leadership can contribute to good safety climate. The managers and leaders shall provide organizational systems and drive the organizational culture that determines not only what people in the organization do, but more importantly, how they do it [37].

5.3. Safety Starts with the Design and Planning Stage

As we know, accidents occur in the production and operation of a chemical enterprise more frequently; therefore, the organization often pays more attention to the safety management work in this stage and ignore the importance of the initial design for accident prevention. Essentially, safety should start with the design stage [45]. Especially for those hazardous chemical production enterprises, the site selection, installations layout and even the design of each process should be considered from the overall safety of the chemical industry park, and the reliability of the design should be continuously demonstrated and improved with the changes of the surrounding environment.

As mentioned above, the safety distance between Shenghua Company and the provincial highway, as well as its surrounding enterprises was far from meeting the requirement of engineering standards. For Shenghua Company, the vinyl chloride gas holders and some hazardous storage tanks were all located on the southern of the plant, only separated by a wall from the Provincial Highway 310. The organization failed to carry out an effective preliminary hazard analysis (PHA) at the beginning of the design and planning of the plant and was not aware of the serious threats that such major hazard installations could pose to the external environment. For the illegal parking lot and Haipoer Company, the construction and operation of their plants were both later than that of Shenghua Company. However, the owners did not take the characteristics of Shenghua Company's production process and the hazards of its intermediate products into account regarding the site selection of their plants and, thus, failed to assess the possible adverse effects on their company in advance.

If Shenghua Company conducted regular safety evaluation on its existing major hazard installations with changes of the external environment, such as the road reconstruction, factory expansion, etc., and further determined the risk radius, they may influence (improve) the original design and strengthen the process management—then the initial leaks might be avoided. If enterprises in the chemical industry park carried out the planning and design in strict accordance with the standards, as well as conducted effective PHA, and maintained sufficient safety distance, then the domino effect, such as this accident, might be avoided, and casualties and property losses would not be so severe. In this case, local government agencies played a vital role in the planning and supervision of a chemical industry park. The land and resources management department shall examine and approve the land used in the chemical industry park strictly, and control the safety distance between enterprises according to regulations. The traffic control department shall standardize the traffic planning of the chemical industry park and try to make the main road not cross or approach the areas where there are major hazard installations. Further, the safety supervision department shall urge enterprises to carry out regular safety evaluations for the status of major hazard installations and, thus, further improve the design and strengthen the risk control.

In order to achieve the centralized parking and management of the vehicles in the chemical industry park, it was necessary for the government agencies to plan and build a specialized parking area. Moreover, the parking lot should have the functions of catering and accommodation to avoid the random parking of the vehicles on the road and the drivers and supercargoes' overnighting in the cab. Meanwhile, in order to ensure the operation safety of the parking lot, the organization shall set up a special safety management department, and allocate sufficient full-time safety management personnel as required. Besides, the parking lot shall establish feasible safety management systems, operating regulations, as well as emergency response plans, and equip adequate fire-fighting equipment and monitoring devices for vehicles loaded with dangerous goods, in such a way to achieve real-time monitoring and systematic management of vehicles.

6. Conclusions

This article performed an investigation and analysis on a catastrophic hazardous chemical accident involving a domino effect by the 24Model, focusing mainly on its process, consequences, and causes classification. Based on this, several important lessons in PSM were summarized, which can be used to avoid similar mistakes in the future.

This accident involved several important organizations and Shenghua Company should be primarily responsible for its occurrence. Several high-risk unsafe acts (e.g., not having the gas holder overhauled within six years, adjusting the return valve of the compressor sharply, parking illegally, etc.) that violated regulations were identified from the organization and concluded as the direct causes of this accident. Unsafe conditions of vinyl chloride gas holders were not discovered and prevented timely due to the nonfeasance of the equipment management personnel of Shenghua Company, in aspects of regular maintenance and overhaul for facilities. The reason for such heavy casualties and property losses was that vehicles from Shenghua Company's suppliers were illegally parked on Provincial Highway 310 that night; there were a large number of drivers resting in the vehicles when the ignition occurred.

The root causes of this accident lie in deficiencies at the organizational level. Shenghua Company shall establish and maintain an effective safety management system in its organizational structure and staffing, safety liability, facilities management, hazards identification, emergency disposal, etc. to improve its safety performance in a systematic and proactive way. Procedures are of no use if they are not well followed. Therefore, the organization should cultivate good safety culture and enable safety values to help members realize the importance of the requirements in the safety management system. Enterprises in the chemical industry park shall enhance the communication and exchange to clarify all major hazard installations in their domains, as well as conduct regular safety evaluation for the plant as the external environment changes. Additionally, related government agencies shall make scientific plans for the layout of the chemical industry park, urge internal enterprises to strengthen hazard identification and risk assessment, and achieve the centralized control of vehicles.

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