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Risk-Based Emergency Management for Production Safety Accidents in Petrochemical Enterprises

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Abstract: The emergency response plan for production safety incidents serves as the core tool for refining and petrochemical enterprises to address emergencies, control incident developments, and mitigate losses. Based on risk management and system safety theories, this paper systematically elaborates on the entire process of developing and dynamically revising risk-based emergency response plans tailored to the production characteristics of refining and petrochemical enterprises. The article first outlines the methodology for risk identification, analysis, and assessment, emphasizing its fundamental importance as the basis for plan formulation. Subsequently, it constructs a three-tiered emergency plan system comprising comprehensive emergency plans, specialized emergency plans, and on-site response plans, detailing their functional roles, core content, and alignment with specific risks. Finally, it focuses on how emergency drills can be used to test and evaluate the effectiveness of these plans, and establishes a scientific, closed-loop mechanism for continuous plan revision based on drill assessments, incident reviews, and risk changes. This research aims to provide theoretical references and practical guidance for refining and petrochemical enterprises in establishing a scientific, practical, and efficient emergency management system.

Keywords: Petrochemical Enterprises; Risk Management; Production Safety Accidents; Emergency Response Plans; Emergency Drills.

1. Introduction

The refining and chemical industry is a pillar industry of the national economy, but its production process is characterized by high temperature and pressure, flammability and explosiveness, toxicity and harm, and strong process chain, with extremely high potential risks. Once a sudden event such as fire, explosion, or toxic substance leakage occurs, it can easily cause significant casualties, huge property losses, and severe environmental pollution. Therefore, building a scientific, efficient, and practical emergency management system is the lifeline for refining enterprises to achieve intrinsic safety and sustainable development.

The quality of the emergency plan for production safety accidents, as a ‘combat plan’ for emergency management, directly determines the response efficiency and disposal effect in the event of an accident. Traditional contingency planning often suffers from problems such as detachment from actual risks, hollow and generalized content, and weak operability. Therefore, the concept of risk-based contingency planning has emerged, which emphasizes that emergency plans must be based on a deep understanding and accurate assessment of their own risks, ensuring that the measures in the plan match the risk level, and that resource allocation is in line with the consequences of accidents.

Focusing on typical production facilities in refining enterprises, this article systematically elaborates on how to build a hierarchical and orderly emergency plan system starting from risk identification, and focuses on exploring a dynamic management mechanism that drives continuous optimization and revision of emergency plans through emergency drills, in order to provide useful reference for improving the overall emergency response capabilities of refining enterprises in China.

2. Production Characteristics and Risk Identification of Refining Enterprises

(1) Typical production equipment and risk characteristics

As the ‘leading’ unit in refineries, the atmospheric and vacuum distillation unit mainly processes crude oil. The risks mainly focus on high temperature, easy corrosion, and easy condensation. Potential accidents include fires caused by leakage of heat exchanger tube bundles, fires caused by coking and burning through of heating furnace tubes, and tower flushing or oil spills in primary distillation towers/atmospheric pressure towers/pressure reduction towers.

The ethylene complex, as the ‘core’ of the chemical park, has a complex process and a long flow. The core risks are ultra-high temperature (about 800 ℃ at the outlet of the cracking furnace), deep cooling (separation system as low as -165 ℃), high pressure (compression system), and handling large amounts of flammable and explosive (hydrogen, ethylene, propylene) and toxic (benzene, hydrogen sulfide) materials. Potential accidents include coking and rupture of cracking furnace tubes, leakage of rapid cooling systems, compressor surge or seal failure, cold box leakage, ethylene ball tank leakage and explosion, etc. The consequences of accidents are extremely catastrophic[1].

Polyethylene plants involve polymerization reactions and have unique risk characteristics. The main risks include: uncontrolled polymerization reaction under high pressure (high pressure process can reach 300MPa) (which may cause explosive polymerization, decomposition explosion), powder explosion (powdery products), and chemical toxicity (catalysts and co catalysts are often flammable or toxic substances when wet). Potential accidents include: reactor pressure runaway and overpressure, reactor temperature runaway, high-pressure polyethylene pipeline rupture, and explosions caused by static electricity in powder silos.

(2) Risk identification, analysis, and assessment methods

Risk identification is the cornerstone of contingency planning. A systematic approach must be adopted to comprehensively identify various hazardous factors and potential accident scenarios

Risk identification methods for refining enterprises:

Safety Checklist Method (SCL): A system hazard assessment method that identifies hazard categories, design defects, and potential risks in engineering systems based on standard specifications. It is applicable to all stages of engineering systems and has the characteristics of foundation, simplicity, and universality.

Job Hazard Analysis (JHA): Divide job activities into categories and decompose them into several steps to identify hazards one by one. Risk quantification adopts the matrix formula R=L × S (where L represents possibility and S represents severity), divides risk levels based on actual conditions, formulates priorities and control measures, and synchronously forms standardized record forms to support safety management.

Hazard and Operability Analysis (HAZOP): Suitable for process industries, it is one of the most effective ways to identify process risks by systematically analyzing the causes, consequences, and existing protective measures of deviations in process parameters (flow rate, pressure, temperature, etc.) through guiding words (such as none, many, few, reverse, etc.).

Failure Mode and Effects Analysis (FMEA): Focuses on analyzing key equipment and instruments, identifying all potential failure modes, and analyzing their possible consequences in order to take necessary measures in advance.

Fault Tree Analysis (FTA): Using logical reasoning to identify and evaluate the hazards of various systems, analyze the direct causes of accidents, and is commonly used in the field of risk management for identifying and measuring enterprise risks.

Risk analysis and assessment: After identifying the accident scenario, a risk analysis is required, usually using the risk matrix method for semi quantitative assessment. Likelihood (L): Evaluate the frequency of accidents, which can be classified into 1-5 levels (such as extremely unlikely, unlikely, possible, likely, frequent). Severity (S): Evaluating the severity of the potential consequences of an accident, including casualties, property damage, environmental impact, and social impact. It is also divided into levels 1-5 (such as negligible, minor, moderate, major, and catastrophic). Risk level (R): R=L×S. Using a risk matrix, risks are classified into major risk, major risk, moderate risk, and low risk levels.

The core of risk-based contingency planning is to develop detailed and reliable emergency response procedures and allocate sufficient emergency resources for major and significant risks identified through assessment. The results of risk analysis directly determine which special contingency plans and on-site disposal plans need to be developed, as well as the specificity and level of detail of their content.

3. Construction of a Risk-Based Three-Level Emergency Plan System

According to the Management Measures for Emergency Plans for Production Safety Accidents and enterprise practices, the emergency plans for production safety accidents in refining and chemical enterprises usually adopt a three-level structure: comprehensive emergency plans, special emergency plans, and on-site disposal plans. The three should be connected vertically and refined step by step.

(1) Comprehensive Emergency Plan

The comprehensive emergency plan is a guiding document formulated from the overall level of the enterprise, and is a general outline for responding to various emergencies. Focusing on ‘overall management and macro management’, addressing the ‘strategic’ issues of emergency management, such as emergency policies, organizational structure, response processes, resource guarantee, and principles of post disaster recovery. Mainly includes:

General Provisions: Purpose, Basis, Scope of Application, Response Grading (Classify accidents based on the degree of harm, scope of impact, and the ability of the enterprise to control the situation).

Emergency organizational structure and responsibilities: Clarify the composition of the emergency command center (and its subordinate working groups for emergency rescue, medical aid, alert evacuation, environmental monitoring, logistics support, information release, etc.), as well as the responsibilities and task actions of each group.

Warning and Information Reporting: Specify the warning level (blue, yellow, orange, red), release procedures, and the process, time limit, and content of accident information reporting (such as reporting to relevant government departments within 1 hour).

Emergency response: Clarify the emergency response initiation conditions and graded response procedures for different levels of accidents.

Post disposal: including post compensation, environmental restoration, insurance claims, emergency assessment and summary, etc.

Emergency support: Plan communication, material, equipment, team, technology, medical, transportation and other support measures.

Combining with risks: Although the comprehensive plan does not target specific risks, its overall framework and resource allocation capabilities must be based on the overall risk assessment of the enterprise. For example, if the major risks of a company are mostly fire and explosion, emergency resource guarantee must attach importance to the provision and maintenance of firefighting forces, leak prevention equipment, medical aid.

(2) Special Emergency Plan

A special emergency plan is an emergency plan developed for a specific type or types of major risks. Functional positioning: Focusing on ‘pipeline and pipe categories’, solving ‘tactical’ problems, providing more specific action guidelines for responding to a certain type of accident, with core content corresponding to risks[2].

For example, the special emergency plan for large storage tank fires and explosions is targeted at the crude oil tanks and intermediate product tanks of atmospheric and vacuum distillation units, as well as the ethylene and propylene spherical tanks of ethylene units. According to the different degrees of tank fire explosion, different stage fire extinguishing measures shall be taken: at the initial stage of the fire, on-site fire extinguishers, fire hydrants, foam hydrants and other facilities and equipment shall be used to put out the fire to prevent the fire from expanding; The fire extended to the storage tank, and the fixed foam fire extinguishing facilities were fully started. At the same time, mobile fire fighting equipment was organized for auxiliary cooling and extinguishing to prevent the explosion of the ignited tank and adjacent storage tanks[3]. At the same time as extinguishing the fire, carry out personnel evacuation and rescue work: determine the evacuation area according to the impact of the accident, set up clear evacuation signs and assembly points, arrange personnel for evacuation guidance, and evacuate the dangerous area in an orderly manner; After arriving at the evacuation assembly point, confirm the number of evacuees and immediately organize a rescue team to search and rescue if anyone is trapped; Set up a temporary medical point on site to provide initial treatment for the injured. Those who are seriously injured should be immediately transferred to nearby hospitals, and the hospital should be notified to prepare for reception.

The special emergency plan for hazardous chemical leakage (poisoning) is aimed at incidents such as hydrogen sulfide and benzene leakage in ethylene plants. When a hazardous chemical leak occurs, first set up an isolation zone, seal off the accident scene, and urgently evacuate unrelated personnel within the isolation zone. Based on the principle of controlling the leakage source and preventing secondary accidents, emergency personnel wear reliable protective equipment to enter the accident site to monitor the concentration of toxic substances in the air, transfer injured personnel, implement leak prevention measures on site, control the leakage source, and recover and dispose of the leaked substances (for flammable and explosive substance leaks, the leaked substances should be dispersed and diluted in a timely manner to prevent the formation of explosive spaces; for water leakage of hazardous chemicals, the government should be notified in a timely manner to prohibit downstream personnel from taking water, monitor the water body, and adopt methods such as salvaging leaked substances, blocking rivers and building dams to prevent pollution from expanding); Transfer the injured person to a place with fresh air, provide on-site first aid according to the severity of the injury, immediately send the seriously injured person to the hospital, and arrange for personnel who may have been affected by the chemical leak to undergo a physical examination afterwards; Establish decontamination stations to disinfect poisoned individuals, emergency rescue personnel, emergency rescue personnel, rescue equipment, etc., control decontamination wastewater, and prevent secondary accidents[4].

The special emergency plan for fire and explosion in production facilities is targeted at core production units such as atmospheric and vacuum distillation units, ethylene cracking units, and polyethylene reactors. When a fire or explosion occurs in a production facility, isolate the accident site first to prevent unrelated personnel from entering the incident area. When there is a leakage of toxic and harmful gases in key areas, toxic and harmful gas monitoring should be carried out simultaneously. Strengthen the personal protection of on-site rescue personnel, provide medical treatment to injured individuals rescued, and immediately transfer severely injured individuals to nearby hospitals. Activate the Emergency Shutdown (ESD) program, cut off the feed pump and close the feed valve, and activate the emergency cooling system. Notify the torch operation position during ESD start-up, confirm the processing capacity of the torch system, control the release flow rate through regulating valves, analyze the composition of the released gas, and adjust the torch operation parameters.

Special emergency plan for long-distance pipeline leakage, cutting off the process flow of production facilities in the affected area to prevent further leakage. After a pipeline leakage accident occurs, strengthen monitoring of adjacent pipelines and take necessary measures to control the leakage; Organize emergency rescue teams to rescue injured personnel at the scene, equip them with various emergency rescue equipment, and request local government participation in rescue if necessary.

(3) On site disposal plan

On site disposal plan is an emergency control measure taken at the initial stage of an accident, targeting specific locations, installations, or positions, specific facilities, processes, or hazards. Focusing on ‘managing points and operations’, solving ‘combat’ problems is the ‘last line of defense’, emphasizing effective disposal at the first time and on the first scene.

The core content corresponds to the risk. Usually in the form of a concise and clear ‘emergency response card’, it is posted on the job site or carried by on-site operators. Following the principle of ‘one case, one card’, taking the ‘on-site disposal plan for ethylene cracking furnace tube rupture’ as an example: rapid increase in furnace temperature, abnormal flame, leakage detected by monitoring, etc; a) Immediately report to the internal operations and team leader, b) activate the emergency stop button, c) wear an air respirator (SCBA) and remotely close the fuel gas manual valve of the furnace. Close the feed valve and open the steam purge valve of the furnace for purging. Evacuate unrelated personnel from the surrounding area and set up a cordon.

The three-level contingency plan system is a whole. In the event of an accident, the on-site disposal plan is activated first. When the on-site disposal plan cannot control the situation, the special emergency plan is activated; If the response procedures of the special emergency plan are not sufficient to solve the accident, the comprehensive emergency plan shall be activated, and external units shall be requested for support to control the situation in a timely manner. From comprehensive emergency plans to specialized emergency plans and on-site disposal plans, the content is refined layer by layer, while also providing emergency resources and guarantees for the site.

4. Emergency Plan Revision Mechanism based on Emergency Drills

Emergency plans are not static files that remain unchanged, and must be tested through practice and continuously improved. Emergency drills are the most important means to verify the effectiveness and operability of contingency plans, train emergency personnel, and achieve dynamic revision of contingency plans.

(1) Planning and Implementation of Emergency Drills

The drill should cover all levels and major risks. The types of drills include desktop simulations, functional drills, comprehensive drills, etc. Desktop simulations simulate the process of responding to production safety accidents according to the clear division of responsibilities and emergency response procedures in emergency plans, combined with relevant experience and lessons learned, gradually analyze and discuss, and form records to test the feasibility of emergency plans. Functional drill is a practical exercise conducted for a certain emergency function (such as communication, evacuation, medical). A comprehensive drill is a comprehensive and full process simulation of emergency response for a major risk scenario, and is the highest form of testing the linkage between three-level contingency plans and government enterprise linkage. The drill plan must be based on real risks and designed with challenging scenarios (such as a leak in an ethylene tank area accompanied by personnel poisoning and changes in wind direction), avoiding formalism of ‘acting for watching’.

(2) Exercise evaluation and plan revision

Management requirements for emergency plans: According to new regulations and requirements in laws and regulations; New regulations and requirements in national standards, industry standards, and local standards; New regulations and requirements in normative documents; New regulations and requirements for upper level emergency plans, and whether adjustments are needed in comparison to the emergency plans.

Main accident risks: Refer to the enterprise risk assessment report and documents related to production operation and process equipment, visit key locations and parts, evaluate whether the identification of accident risks is accurate, whether the level is reasonable, and whether the preventive measures can meet the requirements.

Emergency resources: Review the emergency resource investigation report of the enterprise, compare it with the emergency resource list, check the actual reserve situation of emergency supplies, and communicate with grassroots personnel to evaluate whether there have been significant changes in the quantity, types, and functions of existing emergency supplies, and whether they can actually meet the actual needs of the enterprise.

Emergency plan linkage: Review the emergency plans of superior and subordinate units, relevant government departments, and surrounding enterprises, and evaluate the information reporting, response grading, alert evacuation, and internal and external coordination issues in the emergency plans with relevant personnel.

Implement feedback: Based on the emergency drill evaluation report, emergency response report and other documents, combined with communication and exchange with relevant personnel, evaluate whether there are any adjustments needed in the implementation of the emergency plan.

Revise the triggering mechanism: The conclusion of the drill evaluation is the most direct basis for revising the contingency plan. In addition, the following situations should also trigger the revision process in a timely manner: significant changes in the relevant provisions of the laws, regulations, rules, standards, and higher-level contingency plans based on them; The emergency command organization and its responsibilities have been adjusted; Significant changes in the risks faced by safety production; Significant changes have occurred in important emergency resources; Major issues requiring revision of contingency plans are discovered during emergency drills and accident rescue operations.

Revision process: Establish a standardized PDCA (Plan Do Check Improve) cycle process, and ensure that emergency plans are always in the latest and most effective state through closed-loop management of ‘drill evaluate revise re drill’, truly possessing operability and practicality.

5. Conclusion and Prospect

This article systematically discusses the entire process of developing and revising risk-based emergency plans for production safety accidents in refining and chemical enterprises. Research has shown that risk identification is a prerequisite, and scientific and comprehensive risk identification and analysis (especially the application of systematic methods such as HAZOP), ensuring accurate allocation of emergency resources to major risks, is fundamental to developing targeted contingency plans. The three-level system is a framework that constructs a comprehensive plan, special plan, and on-site disposal plan three-level system, achieving seamless integration of emergency management from macro strategy to micro tactics, in line with the complex and diverse risk characteristics of refining enterprises. The revision of drills is crucial, and the vitality of emergency plans lies in continuous improvement. It is necessary to establish a dynamic revision mechanism based on emergency drills as the core inspection method, combined with accident review, risk changes, etc., to form a closed-loop management and ensure the timeliness, applicability, and effectiveness of the contingency plan.

In the future, with the development of information technology, emergency management in refining and chemical enterprises will become more intelligent and digitized. Smart emergency response will become an important development direction, utilizing digital twin technology to build virtual factories and conduct more realistic and safe emergency simulations and accident consequence simulations in the digital space; By utilizing big data and artificial intelligence to analyze massive risk data, intelligent prediction and warning of risks can be achieved, and emergency resources can be optimized and dispatched, thereby upgrading emergency plans from ‘post event response’ to ‘pre event intelligent prevention and control’ and comprehensively improving the intrinsic safety level of refining and chemical enterprises.

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