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Research on the Improvement of the Safety Management and Control Technology System for Refining and Chemical Industries

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Abstract: Refined and chemical production has the characteristics of high temperature and pressure, flammable and explosive dangers, and intensive exposures to toxic and hazardous materials, typical high-risk characteristics. Plants are running around the clock, the process flows are complicated, the source of hazards is widespread, it is necessary to do a good job in safety management to ensure stable operation and protect the life and property of people. This report lays out a systematic analysis of where we are falling short today with respect to the refining and chemical safety MTTF, summarizes the design guidelines of the system, and refines key technologies in three directions: smart observation and forecasting, online equipment diagnostics, and emergency technology upgrades. Furthermore, it provides long-term protection by means of a standardized procedure, human resource training, and incentive assessment. It is based on practical experience within this industry: the research provides feasible recommendations on how to improve the SMS, which can offer a theoretical basis and reference for building up an advanced safety management system framework, minimizing significant risks, and encouraging effective, long-term safety management within the refining and chemical industry.

Keywords: Refining and chemical industry; Safety management; Technical system; Risk prevention and control

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1. Introduction

The refining and chemical industry is an important component of our national economy. The total production cycle has many high-risk steps, including dangerous chemical storage, reaction process, storage/transportation, in which the safety risk is characterized by suddenness, chain reaction, high explosive yield, and significant destructiveness. With the expansion of refineries and chemical plants, as well as the integration of processing units in recent years, the conventional risk assessment methods based on inspection programs or incident response strategies can hardly meet the requirements of complex production. The existing process safety control systems lack smartness, unplanned risk management, and unstable people's competence, which makes it hard to realize full-process closed-loop control of the whole life cycle. In this context, enhancing the safety control technology system for the refining and chemical industry and advancing its transformation toward intelligent, practical urgency for proactive, systematic efforts in order to avoid safety incidents and assure stable industry operations.

2. Existing shortcomings in the refining and chemical safety management technology system

2.1. The application level of intelligent safety management technologies remains relatively low

Most current refining and chemical enterprises still rely on traditional manual inspections and paper-based records for safety management, with advanced technologies such as intelligent monitoring and automatic early warning systems having limited coverage. Critical high-risk areas, including key production units, storage tank zones, and pipeline corridors, lack comprehensive online sensing equipment, making it difficult to collect and dynamically analyze parameters like temperature, pressure, and gas concentrations in real time. Although some companies have implemented intelligent management systems, issues such as isolated and fragmented systems, incompatible data, and non-compatible platforms prevent the establishment of a unified safety data analysis hub. Consequently, data resources cannot be effectively utilized as decision-making bases for safety management, and the full potential of intelligent management remains unrealized.

The existing safety management technologies mainly monitor each process and do not provide an overall control design for the whole flow. Production safety information, storage, transportation, and discharge activities are fragmented. Upgrades of old refining and chemical facilities have been slow, with a lack of spending on the installation of smart devices; and an attitude within industry that favors output rather than safety improvements. Additionally, there is a shortage of specialized personnel for intelligent management and operations, while equipment maintenance and algorithm optimization fail to keep pace with production demands. This results in underutilized and inefficient smart equipment, hindering the general progress in smart safety management systems.

2.2. The comprehensive risk classification and control mechanism remains insufficiently robust

The refining and chemical industry supply chain is complex, with closely integrated processes that involve vastly differing types of hazards and risk profiles among various sectors. But, the lack of an industry-wide science-based risk categorization system means that most companies do not perform detailed risk identification based on the types of facilities, media characteristics, and operating conditions, leading to very coarse-grained risk categories, which are not easily matched by granular controls. Risk analyses of significant hazards facilities or special operations are sometimes superficial and lack a regular, dynamic risk evaluation and classification updating strategy, which could handle the change of risks caused by varying production status well.

Existing risk control is mainly focused on the production operation stage and not enough attention has been paid to risks occurring under some special time periods, like facility maintenance, expansion/reconstruction, and temporary work, leading to the emergence of control blind spots. The prevention and control of risks are mainly based on post-event rectification, while we lack proactive prediction and source-based prevention principle implementation. No overall risk management process covering risk identification, categorization, hazard mitigation, and closed-loop completion has been developed. Responsibilities between departments regarding risk management are unclear, and coordination is inadequate, resulting in duplication of controls or regulatory gaps and impeding the development of an enterprise-wide risk mitigation program by all employees, all processes, and for all time spans [1].

2.3. The overall competence of the safety professional workforce requires enhancement

Refinery & chemical safety management is a combination of professionalism, technicality, and practicability, requiring some degree of professional knowledge, technical expertise, and sense of responsibility by those engaged in it. At present, there is a large amount of heterogeneity in the professional background of staff members: many team leaders do not have formal training in process improvement, hazardous characteristics of chemicals, and safety technology, rely on their experience in conducting safety management activities; because they lack a high level of skills required to use new safety technologies and smart control devices, they can't adapt to the requirements of modern safety management work.

The company's daily safety education mechanism is not sound enough, and the education contents are too much about theory teaching, lack practical training, smart device application, and emergency drill; the forms of training are boring and not specific enough; employees' safety awareness is low, violating or failing to comply with standards of safe practice by engaging in unsafe conduct. Additionally, the industry lacks robust talent incentive and promotion mechanisms, resulting in severe brain drain among professional safety personnel and insufficient talent reserves, which inhibits safe operations from being continuously carried out by an ongoing, improving SMS.

3. Basic principles for establishing an oil refining and chemical safety management system

3.1. Principle of combining prevention priority with comprehensive process control

The fundamental concept of refinery and chemical enterprise safety management should be prevention-oriented, and the direction of safety control should change from accident handling after occurrence to identifying sources of danger and investigating hazards. by systematically identifying possible risks at every stage of manufacturing, and by implementing risk reduction strategies, safety hazards are eliminated or reduced as much as possible in a process (by means of process engineering, equipment and facilities choice), and/or by organizing work activities so that the risk of accident occurrence is minimized; this shifts from the conventional way of managing safety to a more proactive perspective.

At the same time, we are maintaining a complete closed-loop control over the whole cycle, including in each phase (construction, operation and production, maintenance) of the life cycle of our facilities, active safety management, maintenance, and disposal activities. Such an approach encompasses all of the factors, such as manning, equipment use, environmental monitoring, and material storage and transport, so that there is not a single control point missed. We base ourselves on prevention and full-cycle control, prevent problems from their origin, control them tightly during the process, and provide appropriate assurance at the end point so that there is a continuous, comprehensive safety assurance process in place.

3.2. Principle of synergy between technological empowerment and institutional constraints

The basis of improving safety management practice in the refining and chemical industries will be technological innovation, including the active adoption of new technology such as smart monitoring, online diagnostics, big data analytics, and the Internet of Things to address the limits of human supervision by employing technical solutions, thus enhancing both risk detection capability and risk response effectiveness: Based on the construction of management platform through digitalization and intelligence technology, realizing timely collection, intelligent analysis, and automatic early warning information of safety data can be realized, which provides strong scientific data support to safety decisions.

Institutional development serves as the fundamental guarantee for the standardized operation of safety management. It is essential to establish comprehensive safety management regulations, specific procedures, oversight mechanisms, and performance measures that reflect the nature of the refining and chemicals business. Using technology to boost hardware capability and utilizing institutions as a way of managing behavior, we integrate high technology with standardised management [2]. Relying on technological means to improve the basic facilities of prevention and control, relying on institutional tools to regulate the behavior of cadres and cadre building. We build a shared governance model with technology support and policy protection

3.3. The principle of integrating source control with dynamic supervision

Source control would involve attention to key upstream steps, including refining and chemical industry planning, plant design, and optimisation of the processing steps, raw materials, process layout, and safety facility integration, which will essentially reduce the amount and degree of danger. Strict controls on project qualifications are needed in order to eliminate obsolete, unsafe practices and facilities, improve plant designs, and remove intrinsic safe design defects to reduce the burden of downstream safety control.

Dynamic supervision adapts to the unstable production situation of refining and chemical enterprises and the change of risks at any time. Based on online monitoring devices and a big data platform, it enables real-time monitoring of all production parameters, equipment states, and environmental risks around the clock. The control strategy can be changed according to some conditions, like production loads, weather conditions, and machine deterioration for the timely identification of new hazards. Thus, we can achieve the combination of basic static avoidance and dynamic management by combining the protection mechanism based on the static source with the supervision mechanism of dynamic products.

4. Optimization path for core technologies in refining and chemical safety management

4.1. Widespread integration and application of intelligent monitoring and early warning technologies

Extensively use the Internet of Things, smart sensors, and gas detectors throughout every sector in the oil refineries, as well as chemical industrial parks and manufacturing plants, in dangerous places like reactors, pressure vessels, and pipes, and storage tanks for processed petroleum products, and hazardous chemical warehouses. Deploy smart sensors that monitor the temperature, pressure, liquid level, and leakages of flammable and toxic gas to support continuous automatic data acquisition and real-time reporting of key operational metrics. Using the 5G high-speed communication network to build up the information transmission channel at each monitoring point, centralized fragmented and separate monitoring data to the park's security management system, and realize centralized, visual online supervision of the operation condition in every location, and thus completely replaces the inefficient conventional manual point-checking approach.

Through the application of big data mining and artificial intelligence algorithm technology to build a safety risk analysis model, setting safety threshold values of different process parameters can realize intelligent recognition, tiered evaluation, and auto-pop-up warning of hidden dangers, including the operation status anomaly of facilities, leakage of trace media, and operational parameter variations. An alerting system that provides warnings on a number of channels immediately available at the desk of managers and at remote workstations to workers in the field: mobile apps, and an onsite visual/audio alarm for early detection, early warning, and quick reaction.

4.2. Upgrade of online detection and diagnosis technology for equipment hazards

With the severe service environment that many refining and chemical equipment experience, long periods at high temperature and pressure, corrosive media, and unceasing work, pose a high risk of danger in the form of corrosion damage, loss of operational characteristics, leakage losses, seal failures, and mechanical failures, the desire for on-line diagnostics such as infrared thermography, ultrasonic NDT, vibration spectrum monitoring, and oil analysis. Pressure vessels and heat exchangers, etc., conduct on-line continuous inspection; pump units, pressurized piping systems for the detection of flaws inside pipes, damage on outer surfaces, malfunctioning, and other hidden problems.

Build up the whole life cycle maintenance information base of facilities and equipment, collect operation data orderly, equipment operation state information in real time, the maintenance of equipment record, and the repair record for faults. Through intelligent analysis technology, establish a prediction model for equipment failure trend and make accurate judgment on equipment health condition and residual life. Generate particular predictive maintenance schedules and repair activities depending on the diagnostics results, replacing traditional fixed-cycle maintenance practices and greatly reducing nonproductive time spent inspecting [3]. Technical actions can help avoid accidents like leaks by anticipating the failure of equipment in advance; fires, explosions due to sudden equipment failure, so as to ensure the long-term safe and stable operation of the refining and chemical facility.

4.3. Comprehensive intelligent emergency response technology system

The platform organizes the construction of a unified smart emergency command platform for oil refining and chemical parks, combining multi-functional modules including dynamic risk warning, emergency reserve materials, rescue staff allocation, digital emergency planning, and real-time onsite video streaming. It allows fast reaction, centralized control, coordinated control, and effective crisis response if a crash occurs. A hierarchical classification-based cyber emergency rescue strategy database is constructed based on different accidents (such as fire and explosion), leak of a toxic material, plant closure, and big fire. The system will automatically detect the place where the accident happened and its degree of risk, then suggest best practices in response actions, as well as resources for these activities.

Accelerate the deployment of various intelligent emergency rescue equipment, and promote the use of new technologies such as firefighting robots, unmanned inspection drones, portable emergency gas detectors, and smart life-saving and search-and-rescue devices. All of these technologies would be used to replace human workers at dangerous sites that are either very hot or very cold, contain toxins, and have combustible or explosive characteristics for activities such as in situ detection, firefighting, and risk assessment, thus reducing human losses. Establish a data sharing and emergency linkage system between the enterprise, chemical industrial park, and local supervisory department in order to eliminate the information wall, provide interoperability between first responders, emergency services, and incident management; thus, greatly improving the speed of emergency response, as well as the coordination ability for dealing with unexpected safety accidents

5. Establishment of a long-term mechanism for safety management and control in the oil refining and chemical industry

5.1. Standardized and comprehensive safety control process specifications

By integrating the process characteristics, operational types, and safety regulatory requirements of the refining and chemical industry, a systematic, standardized safety management and control framework covering all production and operational stages has been established. This framework specifies safety standards and detailed control measures for various processes, including raw material storage management, process operation protocols, facility operation and maintenance, hazardous chemical storage and transportation, waste disposal, and special operations. Particular emphasis is placed on refining the approval procedures, operational steps, safety protection measures, and on-site control responsibilities for high-risk operations such as hot work, confined space operations, high-altitude work, temporary electrical installations, and blind flange removal and insertion, ensuring that all operational processes are standardized, regulated, and subject to clear constraints.

Standardize the comprehensive management framework for identifying safety hazards, registering and archiving records, classifying risks by level, implementing time-bound rectifications, conducting on-site inspections, and closing cases through a closed-loop process. Clearly define the rectification timelines, responsible entities, and control requirements for hazards at different levels. Refine the safety responsibility matrices for management, technical, and frontline operational positions at each tier, clearly delineate role boundaries, and enforce a company-wide safety production accountability system. Establish standardized procedures to regulate daily operations, eliminating non-compliant practices such as arbitrary operations, lax management, and overly simplified workflows, thereby advancing refinery and chemical safety management toward full standardization, institutionalization, and routine implementation.

5.2. Routine safety skills development system for employees

Establish a tiered, categorized, precise, and regularized safety training and development system. Tailor differentiated training content and programs based on the distinct roles of safety management personnel, technical staff, and operational workers. Management staff: Concentrate on the theory of safety policy and regulation, control systems design, comprehensive risk control, and integrated coordination management; for technical staff, focus on the professional abilities of using smart surveillance devices, equipment failure diagnosis, use of preventive maintenance technology, and contingency planning; for front-line workers, focus on hands-on training in job operations and safety practices, hazard recognition at the worksite, and self-rescue, mutual rescue under accident conditions.

Try out several learning styles in various formats like remote instruction, face-to-face group classes, on-site practice exercises, drills, and safety case-based alerting learning. Conduct periodic safety skills contests, emergency preparedness exercises, and occupational health training exams [4]. Establish employee personal safety education archives to record the number of hours of training, the content learned during the training period, and the results after training. Establish a system of annual examination and certificate employment, linking evaluation results directly to job assignments, compensation, and performance evaluations, and recognition awards. This continuously enhances the professional competence and safety awareness of all staff, fostering a high-caliber, specialized safety management workforce.

5.3. Multi-dimensional security assessment and dynamic supervision mechanism

Establish a multi-dimensional, quantifiable, comprehensive safety management evaluation system. This system focuses on key dimensions, including application of smart technologies, identification of risks and their elimination, compliance with laws, people's safety awareness level, site operation compliance, and safety control effect. Clear, measurable evaluation criteria have been set up. Regular tiered safety evaluations are conducted for all production workshops, work teams, and on-duty personnel. A system incorporating scoring, ranking, and public reporting of the results is tied in close relationship with performance-based pay for safety assessment, promotions, and other types of recognition. Such a process will provide for accountability in SMS throughout the company.

Establish a sound, regular, and dynamic supervision and inspection mechanism that combines routine inspections, targeted surprise inspections, quarterly full-scale audits, surprise covert inspections, and independent contractor expert reviews as a means of constantly identifying gaps in the safety controls, policy gaps, implementation issues, and onsite non-compliance. Improve the supporting reward and punishment system for safety performance, strictly penalize dereliction of duty, such as improper operations, weak controls, and poor hazard correction, and reward and recognize teams (s) and individuals (s) for exemplary safety performance in managing risks and preventing hazards. Improve safety culture using measures, and hold leaders accountable for failures via oversight, and thus provides the type of durable control system that offers both rewards and limits

6. Conclusion

The overall optimization of the refining and chemical enterprise safety management technology system is an important and systematic work to prevent major safety accidents, preserve industry integrity, and encourage sound industrial development that contributes to the success of businesses, economic development, law enforcement, and safety issues. Prominent issues with current state-of-the-art industrial safety management are the lagging adoption of intelligent applications, deficient categorization of risks, and a lack of adequate manpower expertise. preventative focus; the combined use of technology and institutions; and combining the management of sources with dynamic supervision, to constantly optimize three major technologies: smart monitoring and early warning systems, real-time equipment diagnostics, and automatic emergency response systems.

Disclosure statement

The author declares no conflict of interest.

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