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Petrochemical Plant Emergency Response: Reliability Assessment Using Human HAZOP And AcciMap

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Abstract

In the complex pipeline environment of petrochemical plant workplaces, the risk of fire leading to chain reactions poses a negative impact on human reliability in emergency response. This paper presents a method for assessing human reliability in emergency handling in petrochemical plant areas, using fire as an example. It proposes an approach that incorporates human factors into Hazard and operability analysis (HAZOP) to identify potential human errors and operational mistakes, thereby improving the effectiveness of emergency handling. Previous studies have shown that the standard HAZOP, typically used for process flow analysis, can be effectively adapted to identify deviations caused by human factors. Additionally, Accident Mapping (AcciMap) has been proven effective in capturing softer, intrinsic factors at the levels of government legislation, policy-making, corporate culture, and social management. By utilizing HAZOP analysis to first identify direct human factors that could escalate incidents, and then using AcciMap to identify higher-level human factors and analyze the logical relationships between them, this human reliability assessment model helps understand the root causes of accidents, not just focusing on direct causes such as frontline worker errors. It also considers higher-level factors like government, regulatory, and societal aspects, which are often overlooked in other analysis methods. The study indicates that this model can identify significant human errors impacting fire incidents and provide corresponding improvement recommendations. This aids in reducing the risk of human errors exacerbating or escalating incidents during emergency handling, offering a theoretical basis for designing and managing emergency handling procedures, thus enhancing safety management in the oil and gas industry.

Keywords: human-HAZOP, AcciMap model, human factor, emergency response management, safety management, human reliability

1. Introduction

The petroleum and petrochemical industry is an important energy sector and a cornerstone of industrial infrastructure. Petrochemical plants, as a key link in the conversion chain from raw materials to products within the petroleum and petrochemical industry, are complex and often operate with high levels of risk. Human factors are a primary source of these risks (Dunjó et al., 2020). Additionally, research by Kathleen et al. (2003) indicates that in hazardous situations, human judgment and the ability to act are greatly compromised. Some accidents are exacerbated due to untimely or incorrect responses, leading to more severe consequences. Therefore, studying human reliability in hazardous scenarios can provide a theoretical basis for enhancing safety management in the petrochemical industry, which is of significant importance for the healthy development of the petroleum and petrochemical sector.

The petrochemical industry frequently experiences accidents involving injuries and fatalities, primarily due to events such as fires, toxic gas leaks, and explosions. The dense network of pipes and valves can lead to collateral damage to nearby equipment and pipelines if emergency responses are mishandled, potentially causing more severe accidents. Such incidents are not uncommon. In the Piper Alpha platform incident in the North Sea (Darabon et al., 2020), the failure to remove non-compliant rubber mats after a fire led to the accumulation and burning of spilled crude oil, which heated the natural gas pipelines and triggered the third explosion that sank the platform. In the Bhopal leak incident in India (Basha, 2020), factory managers failed to provide escape information to the surrounding residents, resulting in the death of thousands of people. In these events, humans, as the main agents of production and business activities, are the primary inducing factors of accidents. Various methods have been applied to reduce unsafe behaviors among personnel and to raise safety awareness. However, existing management approaches are insufficient to fully understand the risks. Therefore, a comprehensive understanding of human factors, including workers' unsafe behaviors, decision-makers' improper decisions, and the management at the enterprise level as well as policy and law formulation at the government level, and how they influence an incident, is of great significance for reducing the probability of occurrence and optimizing emergency response when incidents do occur.

HAZOP is one of the widely used mainstream methods for systematic review of risks in chemical processes, and it is a mature qualitative analysis and assessment method. International Electrotechnical Commission (IEC) standardized HAZOP and introduced IEC 61882:2016, which outlines the principles and approach for word-driven risk identification. HAZOP, historically known as a hazard and operability study, is a structured technique for examining a defined system. Its objectives include identifying risks associated with system operation and maintenance, ranging from immediate to wider-sphere hazards, and pinpointing potential operability problems that may lead to non-conforming products. HAZOP studies provide valuable knowledge for determining appropriate remedial measures. In this article, the HAZOP method described in IEC 61882:2016 is considered as the standard HAZOP. Some researches (Yang et al., 2023) showing that the standard HAZOP, after appropriate modifications, can also be used for the reliable identification and evaluation of human factors, with the core purpose of identifying the direct causes leading to the occurrence or escalation of events, namely, employees' unsafe behaviors and unreasonable processes. Based on AcciMap, it identifies higher-level factors in events, such as the company's safety management system, societal safety culture, government policy formulation, and potential factors in legislative institutions, and explores human factors at different levels, from the most direct factors related to workers' behaviors and decisions to the logical connections among higher-level factors. By integrating these factors into a logic diagram, how the factors interact and how they collectively lead to the occurrence or escalation of events will be clearly displayed.

In summary, this article aims to use human factors in the case of fires in chemical plant workplaces as a starting point, attempting to identify the basic events that could lead to the deterioration or spread of events due to all human contributory factors, explore their logical relationships, and propose potential optimization strategies to enhance the safety management level in the chemical industry.

2. Overview of the emergency response human factors reliability assessment model

The assessment model combining Human Factors HAZOP and AcciMap contains four steps as shown in Figure 1:

- Step 1 - Information Preparation. Determine the accident scenarios to be assessed and collect relevant information, including emergency response procedures, laws and regulations, standards, and information on past accidents. Understand and grasp the decisions and actions that personnel need to perform in the emergency response to the accident, and divide the nodes according to human behaviour.
- Step 2 - Human Factors HAZOP Analysis. Select a node and apply Human Factors HAZOP Analysis to it to identify all possible deviations within the node in the form of "action/decision + guide word". Complete the analysis of all nodes in the scenario until all possible human factors biases are identified.
- Step 3 - AcciMap Analysis. Based on AcciMap, explore the deeper human factors such as management and supervision that influence the incident. This includes the level of importance the plant places on emergency response and the completeness of existing plans will affect the management of the emergency response team and equipment, and therefore the safe operation of emergency personnel. In addition, the emphasis placed on safety inspections, contractor management and safety training will directly impact safe operations and equipment condition.
- Step 4 - Optimise to Improve. Discuss whether the existing optimisation and improvement measures in the profile, such as training, development of standard operating manuals, etc., can effectively address the identified human factors biases, and suggest improvement measures for those of them that have a greater impact on the incident.

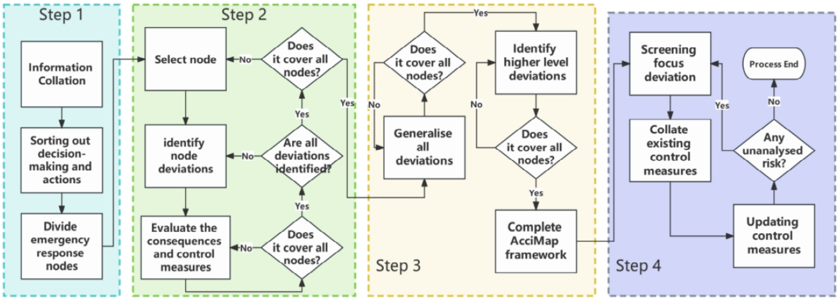

Fig. 1. Emergency response human factors reliability assessment model flowchart.

2.1. Human-HAZOP

Accidents cannot be separated from "individuals - unsafe human behaviour", "equipment - precarious state of machinery, facilities, electrical apparatus, and instruments" and "environment - unsafe circumstances". HAZOP is a widely used international risk analysis method, which can effectively identify and analyse the risks caused by equipment failure or process deviation - "machine" in chemical processes. The HAZOP process is to divide a complete process into several nodes, and within each node, to identify and assess the possible deviations of the node in the form of "parameters + guiding words". However, the application of HAZOP in human factors reliability analysis is far less extensive than the above levels, and there is no uniform standard for human factors HAZOP in the international arena, and scholars have put forward their own views on the application practice of HAZOP in human factors reliability.

According to Baybutt et al. (2002), it was concluded that in industrial practice, human error accounts for anywhere from 50 to 90 per cent of operational risk depending on the industry and level of management, thus making human factors more of a concern than equipment and facility failures in the safety management of chemical companies. However, the core purpose of the standard HAZOP process is to identify, assess and improve equipment failures and process deviations, with a low adaptation to human factors risk. Schurman and Flege (1994) proposed a new approach to incorporate human factors into HAZOP, i.e., by adding new guide words (missing, delayed, etc.) and parameters (people, information and actions) to better meet the requirements of human factors reliability assessment. Although there is no consensus in the academic community on the delineation of human factors HAZOP nodes and the types of deviations, this approach remains the dominant view in the field to date. It has been widely used in recent years in studies such as Fattor et al. (2019) who analysed the human factors and management levels of the Brazilian waste disposal industry by adding new bootstrap terms and identified 209 deviations, Nezamodini et al. (2018) who enabled the standard HAZOP process to be adapted to the human factors reliability analysis by introducing new interpretations of the deviations, and Li et al. (2018) who based on the bootstrap terms and node change proposed a risk assessment system for emergency evacuation of offshore platforms based on the changes of guide words and nodes, which was later applied to the EER HAZOP study for emergency evacuation.

Standard HAZOP is a risk analysis methodology widely used in engineering, with the core task of identifying potential hazards and operational problems, focusing mainly on technical and technological aspects such as equipment failures and process parameter variations. Human Factors HAZOP, however, focuses more on human factors, with particular attention to the impact of human behaviour, decisions and operations on system safety. The conversion from standard HAZOP to human factors HAZOP involves the integration of human factors into the standard HAZOP analysis, which can be achieved by modifying the analysis table of the standard HAZOP or by adding a human factors analysis section, and a comparison table of common terms used in standard HAZOP and human factors HAZOP is shown in Table 1.

Table 1. Conversion of standard HAZOP to human-HAZOP.

Standard HAZOP Terms	Typical Example	Human-HAZOP Terms	Typical Example
Nodes	Piping,heat exchangers,etc.	Emergency Response Stage	Reporting,responding,rescuing,etc.
Process parameters	Pressure,flow,temperature,etc.	Decision/action	Wearing PPE,fire suppression,decision making,etc.
Guide Words	None,less,more,etc.	Guide Words	Confusion,replacement,etc.

Since the objects of the guide words in the standard HAZOP are process parameters, which are quite different from human decisions and actions, and there is no consensus on the guide words required in the human factors HAZOP, this paper reinterprets the seven widely used guide words and adds two new guide words applicable to human activities in the context of the possible actions and related decisions of the personnel in emergency scenarios in chemical plant areas, as shown in table 2.

Table 2. Guide words and explanations in human-HAZOP.

Guide Words	Explanation of Guide Words
None	Failure or inability to implement actions or decisions in emergency response procedures.
Less	Inadequate time or number of actions compared to required emergency response procedures.
More	Exceeds time or number of actions compared to the required emergency response procedures.
As Well As	Perform actions that are not present or prohibited in emergency response procedures.
Part of	The steps required by the procedure are omitted.
Reverse	Perform actions contrary to the requirements of the procedure.
Other than	Unforeseen events.
Unclear	Perform actions in the wrong order or with unclear objectives.
Take place of	Substitution of non-conforming actions.

2.2. AcciMap

AcciMap typically focuses on six Level factors, namely government policy and budgeting; regulatory bodies and associations; local area government planning&budgeting; technical and operational management; physical processes and actor activities; and equipment surroundings (Salmon et al.,2020). In the AcciMap model, the system of control of system risk based on laws, rules, and directives, and information and directives are transmitted unidirectionally in each level respectively, i.e., decisions at higher levels are transmitted to lower levels and influence the behaviour and decisions of lower levels, and information in lower levels is transmitted upwards to provide the basis for decisions at higher levels.

In this case, based on a real event in China as a prototype, and in China, regulatory actions are mostly performed by the local government on behalf of the local government, in addition, there is a clear subordination between company management and local government plans, therefore, the standard AcciMap Levels are appropriately adapted, i.e., merging the regulatory bodies and the local area government planning into one level, and splitting the local area government planning and company management into two Levels.The categorisation of Levels used in this paper is shown in table 3.

Table 3. AcciMap levels.

Level	Common AcciMap Level	Level	Adjusted AcciMap Level
Level 1	government policy and budgeting	Level 1	government policy and budgeting
Level 2	regulatory bodies and associations	Level 2	local area government planning&budgeting,regulatory bodies and associations
Level 3	local area government planning&budgeting,company management	Level 3	company management
Level 4	technical and operational management	Level 4	technical and operational management
Level 5	physical processes and actor activities	Level 5	physical processes and actor activities
Level 6	equipment and surroundings	Level 6	equipment and surroundings

3. Analysis and results

3.1. Emergency response process in a fire scenario

Since the operating sites of each chemical plant are different in terms of process and risk, the fire-fighting measures and emergency plans are also different. The following is a emergency response procedure for a fire case in the Reforming Unit Area of a chemical plant in China.

The complete emergency response process can be divided into several parts, such as checking and confirmation, alarm, disposal, on-site alert, rescue and personnel rescue, on-site monitoring, on-site evacuation and withdrawal, and termination of emergency response. When sound and light alarm signals occur in the plant, in order to prevent false alarms from causing the automatic activation of the firefighting system, the shift supervisor assigns the operator on duty to confirm the fire situation on the spot and then start the "one-minute emergency response" procedure, which includes opening the peripheral firefighting facilities and cutting off the source of leakage, etc., and report back to the shift supervisor. The shift supervisor will report the fire and first aid, and the emergency plan will be activated after reporting to the emergency team leader. In the early stage of fire, if the situation is controllable, the staff on duty will work together with the firefighters to carry out self-rescue and evacuate the unrelated people at the scene. If the Emergency Command judges that the situation is uncontrollable, the employees on duty need to start the self-protection system, make the device into the retreat state, and evacuate to the evacuation point, if trapped on the scene, the firefighters need to assist in the evacuation. When the fire is extinguished, the personnel count is finished, and it is confirmed that there is no risk of reignition of the fire, the end of the emergency disposal process will be declared. The detailed process is shown in Figure 2.

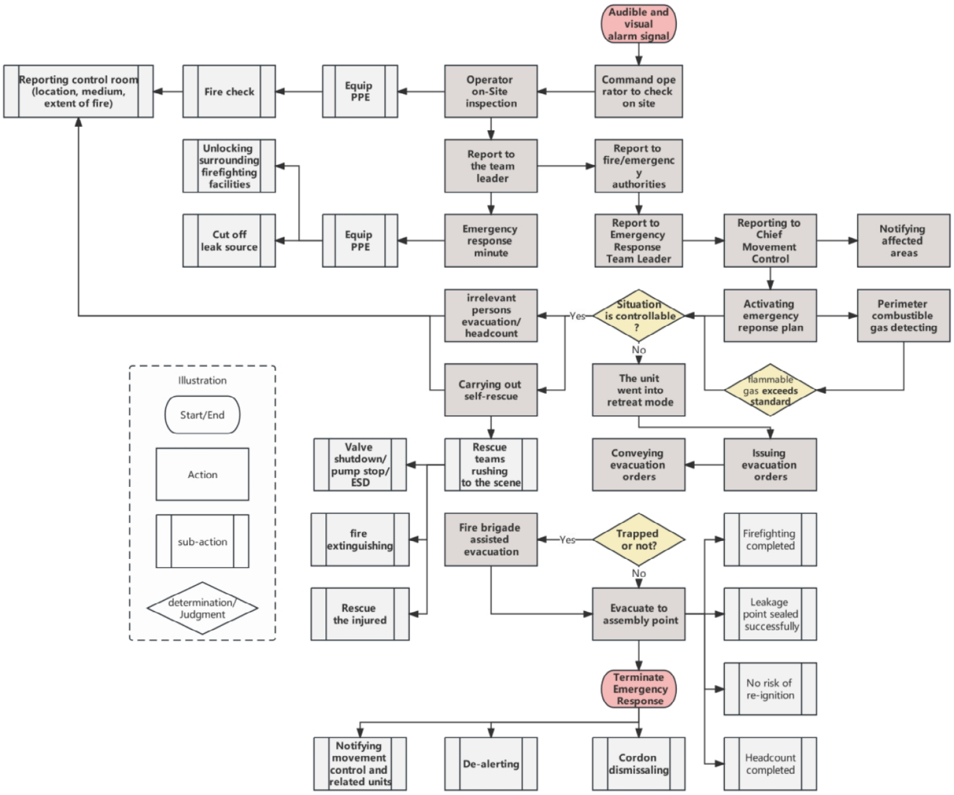

Fig. 2. Emergency response flowchart.

3.2. Emergency human-HAZOP analysis

Based on the step-by-step framework of the human factors reliability assessment model in the previous section, this paper analyses the human factors reliability of the eight links in the emergency response process of the fire scenario in the chemical plant area, such as checking and confirmation, alarming, disposing, on-site vigilance, rescue and personnel rescue, on-site monitoring, on-site evacuation and withdrawal, and termination of the emergency response, and enumerates the possible deviations of the personnel's actions in the emergency response procedure, as well as their potential consequences and probable causes. The results of some analyses are shown in Table 4.

The results show that it is feasible to carry out a qualitative analysis of the human reliability of the emergency response process for fire scenarios in chemical plants based on the human factors HAZOP, and that the potential risks due to human factors can be systematically identified on the basis of the HAZOP analysis table, and the possible causes and consequences can then be analysed, in order to prepare for the development of targeted measures and the improvement of the existing measures and opinions.

Table 4. AcciMap Level.

Emergency Response Stage	Decision /action	Guide Words	Deviation	Possible consequences	Possible causes
Check and confirm	Equip PPE	None	Not wearing PPE	Personnel casualties	Inadequate training/awareness
		Part of	Incomplete PPE		PPE Missing or underestimating the site
		Take place of	Wearing substandard PPE		PPE loss
	Check and confirm fire situation	More	Excessive delay in operations	Fire spreads during operation	Personnel are not familiar with site wiring
		Part of	Not all ignition points identified	Undetected ignition point fire spreads	Lack of adequate manpower/familiarity with the site
	Report	None	out of contact	Personnel panic/extended response time	Communication equipment failure/operational error
		Less	Failure to report all needed information	Failure to obtain key information on disposal	Inadequate training or drills/personnel errors/miscommunication
		More	Simultaneous communications		Panic/lack of process clarity
		Unclear	Unclear reporting		Inadequate training or drills/personnel errors/miscommunication
Personnel evacuation and evacuation	Evacuate to evacuati on point	More	Excessive evacuation time	Casualties caused by explosions or thermal radiation	Failure to follow procedures / unfamiliarity with evacuation routes / crowded evacuation routes / unclear warning signs / unfamiliarity with routes due to inadequate training or drills
		Other than	Accidents during evacuation (falls, blows from objects, injuries from falls, etc.)	Personnel casualties	Crowded evacuation routes / unclear warning signs / unfamiliar routes due to inadequate training or drills
		Part of	Evacuated from work area but not assembled at evacuation point	Impacted personnel counts and caused delays in rescue	
	Fire brigade assists in the	More	Excessive evacuation time	Casualties caused by explosions or thermal radiation	Inadequate rescue equipment or resources / panic / unfamiliarity with the operating environment at the site

	evacuation of trapped people	Other than	Accidents to rescuers or trapped persons (falls, blows from objects, injuries from falls, etc.)	Personnel casualties	Inadequate training or drills/unfamiliarity with site operating environment/personnel panic

3.3. AcciMap Analysis

The AcciMap model in this case is divided into 6 levels, which are government policy and budgeting, local area government planning & budgeting regulatory bodies and associations, company management, technical and operational management, physical processes and actor activities, equipment and surroundings, shown in figure 3.

The AcciMap model for emergency response in petrochemical plant areas is shown in Figure 4, which describes the human factors involved and classifies them into six levels. The first is the level of government policy and budgeting. The soundness of the government safety management system influences the industry safety climate and the responsibility for safety production in chemical plant sites, which in turn affects the emergency response team and resource management. Whether or not the government has developed an emergency response plan will directly affect the safe operation of government responders. Secondly, local area government planning & budgeting regulatory bodies and associations level, whether the government supervision and inspection are in place or not will directly affect the safety management system of the chemical plant area, which is embodied in the qualification of the personnel at the company level and the preparation of the emergency response plan. In addition, the government's review and filing of the plant's emergency plan will further improve the quality of the preparation and implementation of the emergency plan. Thirdly, company management, whether the chemical plant area conducts risk analysis and emergency response for the emergency response process, and the timeliness of its communication mechanism will affect the safe operation of the on-site commanders. The importance the chemical plant area places on emergency response and the completeness of existing plans will affect the management aspects of the emergency response team and equipment, which in turn will affect the safe operation of emergency personnel. Fourthly, the technical and operational management level, Factors at this level are mainly influenced by financial pressures and safety culture in company management, with policy and procedures also contributing more. Fifth, the level of physical processes and actor activities, risk assessment, process compliance and unsafe acts, will also directly affect the safe operations of emergency responders and the condition of equipment. Sixthly, equipment and surroundings, which are mainly affected by levels 3 to 5.

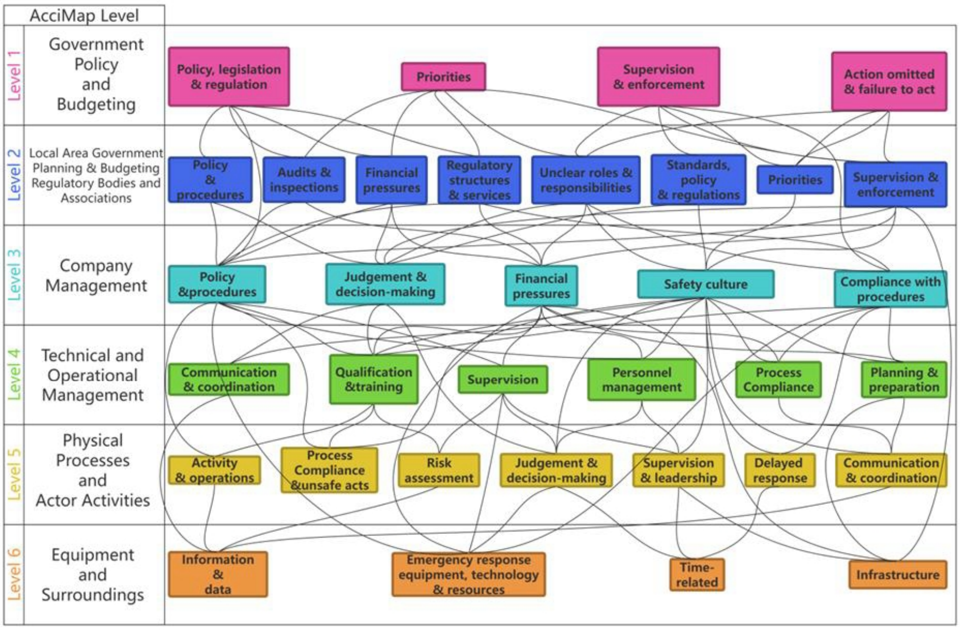

Fig. 3. AcciMap framework based on emergency response to fire in a petrochemical plant area.

4. Discussion

Events that have a greater impact on this scenario include events such as rescuers arriving at the scene late or without adequate equipment, prolonged evacuation time, accidents during evacuation, incomplete sealing off of the scene, wrongly closing/opening of valves during emergency response, and incomplete cutting off of the leak source. If the probability of occurrence of the above events is reduced through management, engineering control and other measures, the probability of deterioration or escalation of events in the event of a fire incident will be effectively reduced.

Enhance training and equipment readiness of rescue personnel: It is recommended that comprehensive training be provided to ensure that rescue personnel are equipped with the necessary skills and knowledge. At the same time, adequate rescue equipment and resources should be secured for quick response in case of emergency. Regularly implement emergency response plan drills, including pre-determined action steps and equipment checks, to improve the efficiency and effectiveness of fire response.

Optimise evacuation strategies and drills: For incidents of "prolonged evacuation" and "accidents during evacuation", it is recommended to develop effective evacuation strategies and conduct regular drills. Ensure that employees know the evacuation routes and assembly points and can evacuate quickly and in an orderly manner during an incident to reduce evacuation time and accidents. Also, conduct regular inspection and maintenance of evacuation routes and equipment to minimise potential risks.

Enhanced site management and monitoring: It is recommended that site management and monitoring measures be enhanced. Introduce automated monitoring systems to detect potential problems in advance. At the same time, strict operating procedures and emergency response plans should be formulated to ensure that they are correctly implemented by operators, and that regular reviews and training are conducted.

Enhance communication and alert systems: Establish efficient communication and alert systems to ensure that all relevant parties can be notified quickly in the event of an emergency. All personnel, including employees, rescue teams and managers, should have a clear understanding of how to respond to alerts and emergency notifications.

5. Conclusion

(1) The perspective analysis of human errors in emergency response procedures, such as inappropriate behaviour and inappropriate decision-making, is conducive to reducing the likelihood of escalation and deterioration of incidents.

(2) The model for emergency response in chemical plant areas based on Human-HAZOP and AcciMap achieves the identification of human errors in emergency response procedures and the logical exploration between the direct causes and the management causes, which provides the basis for the subsequent optimisation and improvement as well as the updating and formulation of emergency response procedures.

(3) The study focuses on the qualitative analysis of human errors in the emergency disposal procedures, and only initially explores the causes of human errors and the possibility of human errors, which need to be studied in depth in the future, in order to further achieve the optimisation of the design of the emergency disposal procedures and safety management.

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