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SEM-based study on the impact of safety culture on unsafe behaviors in Chinese nuclear power plants

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ABSTRACT

This paper uses 135 Licensed Operator Event Reports (LOER) from Chinese nuclear plants to analyze how safety culture affects unsafe behaviors in nuclear power plants. On the basis of a modified human factors analysis and classification system (HFACS) framework, structural equation model (SEM) is used to explore the relationship between latent variables at various levels. Correlation tests such as chi-square test are used to analyze the path from safety culture to unsafe behaviors. The role of latent error is clarified. The results show that the ratio of latent errors to active errors is 3.4:1. The key path linking safety culture weaknesses to unsafe behaviors is Organizational Processes → Inadequate Supervision → Physical/Technical Environment → Skill-based Errors. The most influential factors on the latent variables at each level in the HFACS framework are Organizational Processes, Inadequate Supervision, Physical Environment, and Skill-based Errors.

1. Introduction

The importance of management and organizational factors for the safety of nuclear facilities was highlighted by the Three Mile Island nuclear accident in the United States [1]. Following the Chernobyl nuclear accident in 1986, the International Atomic Energy Agency (IAEA) introduced the term “safety culture” to the nuclear industry to emphasize the significance of management and organizational factors for safety [2]. The 2011 Fukushima nuclear accident further emphasized the need for IAEA safety standards to incorporate lessons learned from accidents that involve human and organizational factors [3]. Safety culture is typically viewed as a component of organizational culture and an essential part of “management and organizational factors” [4]. While major accidents are often attributed to unsafe behaviors by operators, the underlying causes can be traced back to a long-standing safety culture within the organization. Safety culture is vital for the safe operation of nuclear power plants, serving as the primary line of defense against potential accidents [5].

Safety culture is a collection of organizational and individual characteristics and attitudes that determine that the safety of nuclear power plants is valued as a priority because of its importance [6]. Guldenmund believes that there is only a difference in terms between safety culture and safety atmosphere due to different times of popularity and subject areas [7]. The terms are interchangeable. In this study, they are treated as synonymous and does not distinguish between them. Safety culture is both general and abstract. Although safety culture is an invisible abstraction, it can still manifest itself in daily organizational actions, policies, and procedures, which in turn influence the beliefs, and shared values of the organization [8]. Therefore, based on a pragmatic approach, this paper conducts research on safety culture in practice, taking the three important components of organizational structure, culture and process as the observation variables of safety culture. The abstract safety culture can be measured through observation variables, which is convenient for this study to further explore the relationship between safety culture and unsafe behaviors [9–11].

A good safety culture is expected to reduce the rate of human errors and reduce the accident rate of factories [12–15]. Poor safety culture in nuclear power plant systems may cause two types of errors: active errors and latent errors [16]. Active errors are actions or omissions that immediately negatively affect front-line workers (i.e., actors who directly see and influence the process in question) at the sharp end of the organization (the human-machine interface between the organization and the system) [17]. It is usually manifested as unsafe behaviors of the person and directly causes the

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occurrence of the incident. Latent errors, on the other hand, lie in the system for a long time, long before the destructive consequences occur. Latent errors are closely related to the managers, designers, maintainers, or regulators at the blunt end of the organization [18,19].

Latent error is one of the major factors causing accidents [16]. Poor safety culture may lead to latent errors. Latent error that arises from higher levels of the organization creates preconditions for unsafe behaviors indirectly, which in turn leads to operators' unsafe behaviors. Other studies have shown that safety culture is closely linked to organization and management, indirectly related to the regulatory environment, and has a significant impact on unsafe behaviors and latent errors of personnel [21]. Reason's Swiss cheese model is a defense system for organizing activities based on the four dimensions: organizational factors, regulatory environment, preconditions for unsafe behaviors and unsafe behaviors [16]. It is a four-tier defense system for organizing events. Danger can only occur if a flaw or vulnerability in an event evades the defenses and obstructions of a four-tier protection system. Human Factors Analysis and Classification System (HFACS)framework taking Swiss Cheese Model as its foundation, combines the above levels and uncovers the underlying causes of safety culture in events from the perspective of sharp-end human behaviors. The HFACS framework is one of the most widely used and effective models in the field of human errors[22–24]. The HFACS framework narrows the gap between theory and practice by providing safety professionals with theoretical-based tools to identify and classify human error in accidents. This study chose HFACS (Human factors analysis and classification system) as a tool to study the safety culture of nuclear power plants, which can help identify the root causes of human error [25].

In general, HFACS is used as a retrospective tool for analyzing accident and incident reports. Although intended for aviation accidents, it is currently being used in a variety of fields to explore organizational safety management in complex systems, including rail transport [26], aviation [27], maritime accidents [28], mining [29], etc. Kim et al. used the HFACS model to explore the interrelationships between organizational factors in the nuclear industry and developed strategies to prevent human error in nuclear power plants [30]. Yoon et al. proposed a new model and method for analyzing human factors events based on the HFACS model and activity theory, and successfully verified it using the case of nuclear power plants [31]. Karthick et al. used the HFACS model combined with the FAHP method to explore human error in the main control room of nuclear power plants, and the study showed that this method can be used to determine the intrinsic human factors of nuclear power plant master control room operators [32]. These studies demonstrate the HFACS framework's reliability in researching human errors across various domains, including nuclear power plants, and provide strong evidence supporting its use for such analyses.

In the later research of the HFACS framework, the researchers shifted the focus to quantitative analysis of the relationship between the influencing factors in accidents, combining the HFACS framework with other quantitative analysis methods, such as Bayesian networks (BN) [33], Neural Networks (NN) [34], Analytic Network Process (ANP) [35], etc., to reveal the important factors affecting accident safety. Structural Equation Models (SEMs) have the capability to simultaneously process multiple sets of variables, even when these variables contain measurement errors. Additionally, SEMs can estimate the structure between factors, as well as the relationships between these factors and the overall model fit. The correlation method used in this paper is well-suited to elucidate the causal relationships between variables based on the statistical analysis of categorical data. Therefore, the structural equation model and correlation analysis method is selected to analyze the HFACS framework. Through them, the interrelationship between the latent variables can be clearly observed in organization. The path and key factors of the event can be determined to make suggestions on the reduction of human errors and promote the safe operation in a nuclear power system.

2. Methods

2.1. Human factors analysis and classification system (HFACS)

The HFACS model refines the four levels of the Swiss cheese model. HFACS framework categorizes the causes of accidents into 18 causal categories at 4 levels. From bottom to top is unsafe behaviors of frontline operators of the organization, preconditions for unsafe behaviors, unsafe supervision of managers and safety culture at higher levels of the organization. The influencing factors of subcategories are elaborated at each level. In this model, active errors of frontline operators are combined with latent errors in the dormant state of the system, breaking through tissue barriers and ultimately leading to accidents. These latent errors arise at the top of the organization and are related to the management and governance structure. The framework involves two types of errors: latent errors and active errors. The bottom level of unsafe behaviors is mostly active errors, the other three levels on the top are latent errors [16]. When latent errors and active errors are combined, under the action of triggering factors, the barrier of the system will be broken resulting in the occurrence of incidents or accidents.

Since the original framework could not fit the results of the event report analysis well, in order to adapt it to the characteristics of nuclear safety culture in practice, the three factors of physical/mental limitations, adverse mental states and adverse physiological states that were not very observable in the event reports in the original HFACS framework were not included. And in order to apply this model to the nuclear domain, terms of a different general nature in aviation were modified. After repeated revisions, the HFACS framework suitable for the analysis of safety culture in nuclear power plants is finally determined in Fig. 1.

2.2. Correlation and path analysis methods

The HFACS model focuses on comprehensive qualitative analysis. On this basis, this paper introduces Structural equation model (SEM) to analyze the impact of safety culture on unsafe behaviors.

Structural equation model mainly refers to the statistical method of analyzing the relationship between variables through the covariance matrix of variables[36,37]. It is one of the most popular methods to deal with the complex relationship between latent and observed variables, which is common in accident analysis. Many previous studies have used structural equation models to explore the influence of safety atmosphere on safe behavior in container transportation environment and the influence of safety culture on unsafe behaviors in maritime transportation[38,39]. Moreover, the researchers have verified the impact of safety leadership, situational awareness, and security awareness on unsafe behaviors[40–42]. In this paper, based on the HFACS, the relationship between safety culture and unsafe behaviors is studied. MPLUS software is used to analyze the structural equation model that affects the unsafe behaviors of nuclear power plant[43,44].

Then, the chi-square test is used for independence test [45]. The independence between factors is analyzed and non-independent factors are found. On this basis, the selected factors are analyzed by asymmetric forms of Lambda correlation measurement method and Tau-y correlation measurement method to determine the degree of correlation between factors and the influence path[46,47].

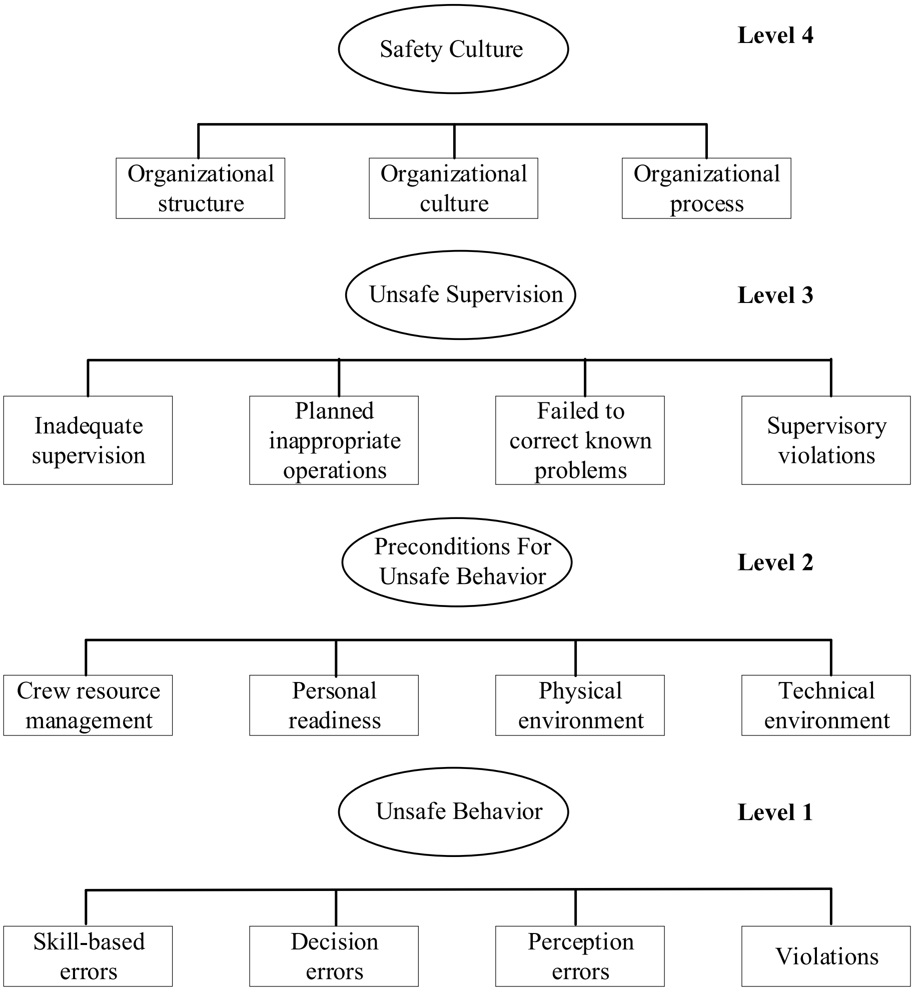

Fig. 1. Revised HFACS framework.

Since the variables reported by the analysis events are categorical variables, the values of categorical variables have no numerical meaning, and "0" and "1" are used to indicate the state of variables. Furthermore, the directional correlation coefficients of measuring categorical variables, Lambda coefficient and Tau-y coefficient, can be used to observe the correlation between influencing factors at adjacent levels, thus obtaining the transmission path from safety culture to unsafe behaviors[48,49]. It should be noted that the Lambda correlation measurement method uses the majority value as the prediction criterion. It does not take into account the number of times distribution other than the common value, so there may be a sensitivity defect. That is, when the coefficient is equal to 0, there is still a correlation between the variables. In response to this situation, Goodman and Kruskal's Tau-y correlation measurement method will also be used in the correlation analysis [50]. The Tau-y coefficient is an asymmetric correlation measurement method. It is based on all the number of edges and the number of conditions. Its sensitivity is higher than that of the Lambda coefficient, which can compensate for the shortcomings of the Lambda coefficient to a certain extent.

In this context, this study integrates HFACS model and SEM analysis to explore the influence relationship between safety culture and unsafe behaviors in nuclear power plants. The remainder of this paper is arranged below. Section three is an introduction to the preliminary statistical results of the incident report. In the fourth section, SEM, chi-square test, lambda and tau-y correlation coefficients are used to analyze the correlation and path of factors between different levels. Section five presents conclusions and discussions.

3. Event report collection and analysis

The research initially collected 150 LOERs from Chinese nuclear power plants between 2006 and 2017. Out of these reports, 15 were screened out as they were related to equipment failures such as pipeline cracks, heat transfer pipe damage, chip failure, short circuit, and weld area leakage. These 15 reports did not involve any observable human errors, making it impossible to analyze safety culture and organizational management and were thus eliminated. The remaining 135 reports were used for further research on human error-related events. The observable items in these 135 event reports were classified according to the four levels defined by HFACS. The presence or absence of items in the event reports were counted, and each event report was only counted once for the same causative factor.

3.1. The event report called "Unit 1 of the nuclear power plant opened the reactor for longer than expected"

A detailed event is presented for the purpose to show how event report is analyzed. The event " Longer time than expected to open the reactor cover" took place in a cold shutdown state. The main information of the event is summarized below:

During outage, the reactor was being overhauled. The stretching machine was ready to attach the top cover spreader to lift the top cover and fill the pool with water.

At 23:40 midnight, the shift team arrived at the field site to take over the shift and conducted a pre-job briefing. Then the team started connecting the top cover spreader with a ring crane.

At 00:15 in the morning, the ring crane driver was in the ring crane cab and cooperated with the field lifting command to connect the top cover spreader.

At 00:30 a.m., after the connection between the ring hanging main hook and the top cover spreader was completed, the fixing pin needed to be pulled out. The lifting command signaled the ring crane driver to jog up so that the retaining pin is free for easy removal. The lifting command then made a stop gesture. The ring crane driver did not see the stop signal and at this time heard the abnormal sound of the ring crane. He glanced down. After looking in the direction of the cab door, the ring crane driver heard a second thud and immediately stopped the operation.

At 00:31 a.m., the inspection revealed that one of the fixed foundations of the fixed roof spreader had been displaced upwards and that about one square meter of concrete on the ground below was damaged.

Once you have an in-depth understanding of the overall event report, categorize them by main and subcategories of the HFACS framework. Table 1 is obtained.

3.2. Descriptive statistical results

135 event reports are analyzed according to the analysis process in the above exemplified case. The factors present in the event reports are marked as 1, and the factors that do not exist are marked as 0. Finally, the frequency of HFACS framework factors in all event reports shown in Fig. 2 and Tables 2–5 are obtained.

3.2.1. Safety culture

The weakness of safety culture arises from the blunt end of the organization and is closely related to the strategic decision-making and the formulation of rules and regulations by senior managers. The concept of this level is to embed safety culture into organizational management practices. It takes the three factors of organizational structure, organizational culture and organizational process as the representation of safety culture in nuclear power plant events. Organizational structure is the formal framework of an organization that defines how and by whom it is done. In this paper, the lack of manpower, funding, equipment, facilities, etc. of nuclear power plants will be regarded as a loophole in the organizational structure of the safety culture. From Table 2 we can find the following. Organizational culture is the lack of understanding of the safety culture elements of the organization members, which appears in the event reports, examples are insufficient understanding of the severity of the performance degradation of electronic components caused by the aging of relays, and the lack of questioning work attitude of the person in charge of the implementation and review. The organizational process is mainly measured by checking whether there are deficiencies in the relevant rules and regulations of the nuclear power plant. It is related to the tactics and strategy of the organization. It often appears in the event reports, examples are insufficient procedures, electrical test procedures do not have requirements for verifying the interlock protection channel; no risk alerts for accidental bumps in the risk analysis of the work package. Among the three, the organizational process occurs most frequently, accounting for 56.3% of the total number of incidents, and the organizational structure and organizational culture account for a smaller proportion, reaching 39.26% and 34.81% respectively. It shows that the rules and regulations in the nuclear power plants are the most prone to problems.

3.2.2. Unsafe supervision

The level of unsafe supervision includes four categories: inadequate supervision, planned inappropriate operations, failed to correct known problems and supervisory violations. Through Table 3 and the analysis of the event report, we can find the following. Inadequate supervision refers to the supervisor's failure to perform supervision in accordance with the requirements of rules and regulations, examples are the person in charge of the work is not on site and cannot supervise and guide the cleaning personnel; the person in charge and guardian of the work violated the provisions, failed to perform the online inspection of on-site instruments in accordance with the requirements of the actual work package, and there are frauds and concealment of reports in the work. Planned inappropriate operations refers to unreasonable staffing or work arrangements, examples are improper arrangement of isolation manager's elimination work window on the non-main line; the schedule for restoring the unavailable equipment is not well controlled and the on-site work schedule is under great pressure. Failing to correct known problems means that the supervisor does not find hidden dangers or does not correct them in time after discovery, examples are the design review process does not identify the defects in the design of the nitrogen seal pipeline of the main pump; during the regular inspection, it is found that the local overheating of the relay caused the discoloration of the clamp, but the relay cannot be replaced because there were no enough spare parts. At this level, the proportion of inadequate supervision and failed to correct known problems reach 50.37% and planned inappropriate operations and supervisory violations are small, 25.93% and 14.81% respectively.

Table 1
Decomposition of the event “Unit 1 of the Nuclear Power Plant opened the reactor for longer than expected”.

Level	Factor	Content	Error type
Safety culture	Organizational culture	Due to the inappropriate position, when the lifting command sent a gesture signal to jog upward, the ring crane driver needed to look down to confirm the signal, but the ring crane driver did not object to this, nor did he remind the lifting command to reposition the station–lack of questioning attitude	latent error
Preconditions for unsafe behaviors	Crew resource management	Insufficient communication between the lifting command and the ring crane driver	latent error
	Physical environment	It is dark on site, making it difficult for the ring crane driver to see the lifting command gesture	contributing condition
Unsafe behaviors	Decision errors	The position selected by the lifting command was not suitable, making the ring crane driver prone to misjudgment	active error
	Perception errors	The ring crane driver mistakenly saw the electric signal of the lifting command gesture as a slow rising signal	active error
	Violations	The ring crane driver still operated when he could not see the lifting command gesture signal, which violated the “Crane Safety Operation Regulations"	active error

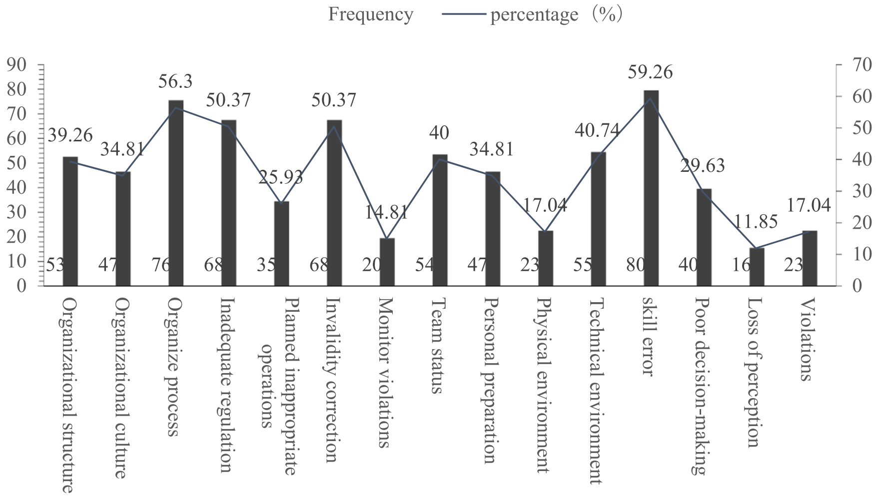

Fig. 2. 135 events reported HFACS category frequency and frequency counts.

Table 2
The frequency statistics of safety culture level.

Level	Factor	Description	Frequency	Percentage(%)
Safety culture	Organizational structure	Allocation and management of manpower, capital, equipment and facilities, design and other aspects of nuclear power plants	**53**	**39.26**
		The control of the work process is not in place	26	19.26
		Management strategies are not perfect	19	14.07
		Inadequate O&M management	7	5.19
	Organizational culture	Members of the organization do not have a good understanding of the elements of safety culture, such as: safety management structure, leaders' decisions, values, beliefs, attitudes	**47**	**34.81**
		Overconfidence and lack of questioning	24	17.78
		Insufficient awareness of risks and weak awareness of prevention	23	17.04
	Organizational processes	Whether there are deficiencies in the relevant rules and regulations of nuclear power plants	**76**	**56.3**
		The procedural system is not perfect	64	47.41
		Procedures are not perfect	14	10.37
		There is a problem with the quality of the working documents	12	8.89

3.2.3. *Preconditions for unsafe behaviors*

The preconditions for unsafe behaviors include four categories: crew resource management, personal readiness, physical environment and technical environment. Through Table 4 and the analysis of the event report, we can find the following. Crew resource management refers to the team's own safety education, skill training and communication and cooperation with other teams, examples are the telephone communication process between radiation protection site personnel and radiation protection duty room personnel, not use three-phase communication technique resulting in communication failure; inadequate training on risk isolation preparedness. Personal readiness refers to the staff's own readiness before work, examples are blind knowledge spots, misunderstanding of internal parameters; work instructions and corresponding drawings were not prepared in advance. The physical environment refers to the environment around the staff, examples are the scaffolding operation space is relatively narrow and the probability of accidental collision increases; the work site is noisy and the broadcast content cannot be heard clearly; line trip due to a wildfire outside the plant resulting in a loss of power supply. Technical environment refers to equipment failure, device failure and other technical factors that affect the environment, such as equipment and control design, display and interface design, automation design, etc., such as: relay export card aging failure; defects in the design and manufacture of casings, etc. At this level, the proportion of technical environment, team status and personal preparation is relatively large, 40.74%, 40% and 34.81%, respectively, and the proportion of physical environment is small, 17.04%.

3.2.4. *Unsafe behaviors*

Unsafe behaviors mainly occur with frontline operators at the sharp end of the organization. Most of the them are active errors including skill-based errors, decision errors, perception errors and violations. Through Table 5 and the analysis of the event report, we can find the following. Skill-based errors refer to ones with operator operation technology, and of self-correction skills, etc., such as errors due to inattention, memory failure and poor technical quality. Typical examples in the event reports are that the I&C personnel omitted to pull out the safety latch after the work is completed resulting in the loss of spray function; the system temperature sensor is installed in the wrong position due to operators' lack of skills. Decision errors refers to those that does not meet the requirements of rules and regulations or actual conditions when performing tasks, examples are the commissioning personnel does not comply with the TCA management process and the double confirmation work system; operating the electrical and mechanical gate switches without the permission of the guardian. Perception errors refers to the deviation between the perception

Table 3
The frequency statistics of unsafe supervision level.

Level	Factor	Description	Frequency	Percentage(%)
Unsafe Supervision	Inadequate supervision	(Supervisors) fail to perform supervision in accordance with the requirements of rules and regulations	68	50.37
		The implementation of supervision and inspection work is not in place	60	44.44
		Failure to provide supervision and guidance	8	5.92
	Planned inappropriate operations	Inadequate staffing or work arrangements	35	25.93
		Improper arrangement of work windows	23	17.04
		Inadequate risk analysis	10	7.41
		Frequent personnel changes	2	1.48
	Failed to correct known problems	The supervisor did not find hidden dangers or did not correct them in time after discovery	68	50.37
		Failure to identify hazards	63	47.73
		Failure to correct known defects in a timely manner	5	3.7
	Supervisory violations	Supervisors deliberately ignore or violate existing rules and regulations	20	14.81
		Supervisors fail to perform supervision as required	16	11.85
		Supervisors intentionally violate supervision requirements and regulations	4	2.96

Table 4
The frequency statistics of preconditions for unsafe behaviors level.

Level	Factor	Description	Frequency	Percentage(%)
Preconditions For Unsafe behaviors	Crew resource management	The team itself receives safety education, skills training, and communicates and collaborates with other teams	54	40
		Communication understanding is not in place	33	24
		If three-stage communication is not used, the means of communication are ineffective	5	3.7
		Insufficient team training	9	6.67
		Experience feedback is not in place	7	5.19
	Personal readiness	The staff's own readiness before work	47	34.81
		Insufficient skills and knowledge of personnel	41	30.37
		Inadequate personal work preparation	6	4.44
	Physical environment	Surroundings of the staff	23	17.04
		Foreign invasion, such as: dust, seaweed, air current, etc	13	9.63
		The working space is cramped/poorly lit/unreasonably arranged	10	7.41
	Technical environment	Equipment failure, device failure and other technical factors that affect the environment, such as equipment and control design, display and interface design, automation design, etc	55	40.74
		The equipment has quality defects, failures	28	20.74
		Unreasonable design/design flaws	27	20

Table 5
The frequency statistics of unsafe behaviors level.

Level	Factor	Description	Frequency	Percentage(%)
Unsafe behaviors	Skill-based errors	Errors in operation technology, self-rescue skills, etc., such as inattention, memory failure, and poor technical quality	80	59.26
		Inappropriate operation	76	56.3
		Misunderstanding and memorization of work content	14	10.37
	Decision errors	The decision-making when performing the task does not meet the requirements of the rules and regulations and the actual situation	40	29.63
		Decisions are not strictly followed by institutional procedures	25	18.52
		Errors of judgment in specific situations	15	11.11
	Perception errors	The perception and understanding of objective things deviate from the actual situation (the operator's perception ability is reduced in a bad environment, and then perceptual errors occur)	16	11.85
		Personnel are affected by experience, stress and emotions to make mistakes in judgment	13	9.63
		Personnel are interfered with by the external environment and misjudged	3	2.22
	Violations	Violations of safety regulations that may lead to accidents	23	17.04
		Habitual violations	15	11.11
		Incidental violations	8	5.93

and understanding of objective errors and the actual situation, especially in a harsh environment, resulting in a decrease in the operator's perception ability, examples are the ring crane driver sees the jog signal of the lifting command gesture as a slow rising signal due to too dark lighting on the spot. Violations refers to the violation of procedures and regulations, including habitual violations and accidental violations, because the two occur less frequently, so they are merged into the one variable, examples are skipping the procedure steps, contractors' habitually violation of the rules. At this level, the proportion of skill-based errors is 59.25%, followed by decision-making errors, violations and perception errors, accounting for 29.63%, 17.04% and 11.85% respectively.

4. Analysis of the influence path of safety culture on unsafe behaviors in nuclear power plants

4.1. Model fit test and correction

Based on the revised framework, this paper establishes a confirmatory structural equation model of human errors in nuclear power plants and explores the interaction relationship between 15 factors at 4 levels in the HFACS framework.

AMOS software is often used to process continuous variables. MPLUS Software is a powerful latent variable modeling software that can process the categorical variables. This paper uses MPLUS software for structural equation model verification. The main model fitting index output by the software for categorical variables is NC value (chi-square/degree of freedom), chi-square value, CFI value, TLI value, and RMSEA value. The above metrics are commonly used to assess the goodness-of-fit of a constructed model with observed data in SEM research. Chi-square statistics often obtain significant Chi-square test results due to sample size, data distribution morphology, etc. in research. Researchers often choose to ignore the significant chi-square difference test results and consider other fitting indices as the basis for accepting the model. Therefore, although the P-value of the chi-square test in this study is 0.0305, it is still considered that the model of this study is true. RMSEA(Root Mean Square Error of Approximation)is a measure of the discrepancy between the predicted model and the observed data. It is generally considered that the indicator less than 0.01 fits very well, less than 0.05 fits well, and less than 0.1 fits acceptable. In this study, the fitting value of this index is 0.048, which is a good fit. CFI(Comparative Fit Index) is one of the most commonly used goodness-of-fit indices in SEM. The CFI is calculated by comparing the fit of the hypothesized model to a null model, which is a model that assumes no relationships between the observed variables. This fitted index greater than 0.9 is generally considered acceptable. In this study, the value of CFI reached 0.925, which is acceptable. TLI(Tucker-Lewis Index)is an important tool for evaluating the validity of SEM models. It is generally considered acceptable that this fitted index greater than 0.9 is acceptable. In this study, the TLI reached 0.906, which is acceptable. In order to correct the effect of degrees of freedom on chi-square, the ratio of chi-square to degrees of freedom is often used to evaluate model fitting. It is generally believed that $1 < NC < 3$ indicates that the model has a degree of simple adaptation. $NC > 5$ indicates that the model needs to be corrected. In this study, $NC = 1.3$, which is acceptable. At the beginning of calculation, the correlation coefficient of this model is slightly greater than 1. Considering the collinearity problem of variables, the original model is revised and finally the modified model is obtained. The indicators of the revised model are better than the pre-correction model and meet the index standards shown in Table 6.

4.2. Analysis results of HFACS path of nuclear power plant based on SEM model

Combined with the analysis results of the event reports, the weighted least squares method (WLSMV) [51]suitable for categorical variables is used in the structural equation model operation, and the correlation path diagram between each level of HFACS is obtained, as shown in Fig. 3. When the significance level is 0.05, the numerical distribution of the 15 factor loading coefficients in the model is between 0.298 and 0.986. The basic adaptation of the model is good and has high structural validity. The number in parentheses represents the standard error, also known as the sampling standard error, which is the standard deviation of the sample statistic and measures the dispersion of the sampling distribution. Based on the fitting degree analysis of the comprehensive model and the HFACS path diagram of nuclear power plants, it can be seen that the revised HFACS framework has good applicability to the analysis of human error factors in nuclear power plants.

The results of path structure analysis show that there is a positive correlation between all latent variables. The change of any latent variable will affect other latent variables. In the structural equation model, the factor loading coefficient between the safety culture and preconditions for unsafe behaviors reaches 0.829. The factor loading coefficient for safety culture and unsafe behaviors of operators reaches 0.677. The factor loading coefficient for unsafe supervision and preconditions for unsafe behaviors reaches 0.615. The factor loading coefficient of the preconditions for unsafe behaviors and unsafe behaviors of operators is 0.711. The correlation between the latent variables mentioned above is strong, all reaching a strong correlation of more than 0.6. Comparing the path coefficients of the 15 observed variables. It can be seen that the organizational process (0.655), inadequate supervision (0.986), physical environment (0.625) and skill-based errors (0.824) of the four levels are the factors that have the greatest impact on the observed variables at each level.

An interesting point is that physical environment and technical environment are negatively correlated with the latent variable of preconditions for unsafe behaviors. Looking at the statistical results of the event reports, it can be found that physical environment and technical environment occur less frequently at the same time as the crew resource management and personal readiness within the same level. Environmental impact may have a negative correlation with crew resource management and personal readiness within the same level. This means that in the 135 event reports, when the second level of environmental failures caused the event, the crew resource management and personal readiness are relatively good. At the same time, when an event occurs due to crew resource management and personal readiness, environmental factors have less negative impact. Environmental factors, as the factors with the greatest impact at this level, should attract sufficient attention.

In the HFACS framework, when errors occur at all levels at the same time, the multi-level defense of the system would be broken and accidents may happen. Therefore, through path analysis, the key paths to summarize the impact of weak safety culture on unsafe behaviors in nuclear power plants is: organizational processes→ inadequate supervision → physical environment → skill-based errors.

4.3. Human error transmission paths in nuclear power plants

The above application of structural equation model to verify the HFACS framework can only obtain the degree of interaction between the levels. It is not directional. Therefore, the next step is using $\chi 2$ (chi-square) test for independence test. For the independence between factors correlation analysis, we get $\chi^2 = 3.84$ at the significance level $\alpha = 0.05$. When the actual value of χ^2 is greater than 3.84, it is believed that the two factors are interdependent and related [45]. So non-independent factors are found. On this basis, these selected factors are analyzed by directional Lambda correlation measurement method and Tau-y correlation measurement method to determine the degree of influence and transitivity between adjacent level factors, which is also in line with the theory of top-down causes analysis in the HFACS framework. The results are shown in Table 7. The letters ABCD represent the four levels of safety culture, unsafe supervision, preconditions for unsafe behaviors and unsafe behaviors. In addition, A1 represents organizational structure. A2 represents organizational culture. A3 represents organizational process; B1 represents inadequate supervision. B2 represents planned inappropriate operations. B3 represents failed to correct known problems. B4 represents supervisory violations; C1 represents crew resource management. C2 represents personal readiness. C3 represents physical environment. C4 represents technical environment; D1 represents skill-based errors. D2 represents decision errors. D3 indicates perception errors. D4 indicates violations.

Fig. 4 yields the transmission path between factors at adjacent

Table 6
Fitting index of HFACS factors after revision.

Evaluation indicators	Absolute fit index		Value-added suitability index		
	Chi-square value	RMSEA	CFI	TLI	NC
Standard value	P > 0.05	< 0.08	> 0.9	> 0.9	1 < NC < 3
Revise model metric values	0.0305	0.048	0.925	0.906	1.3

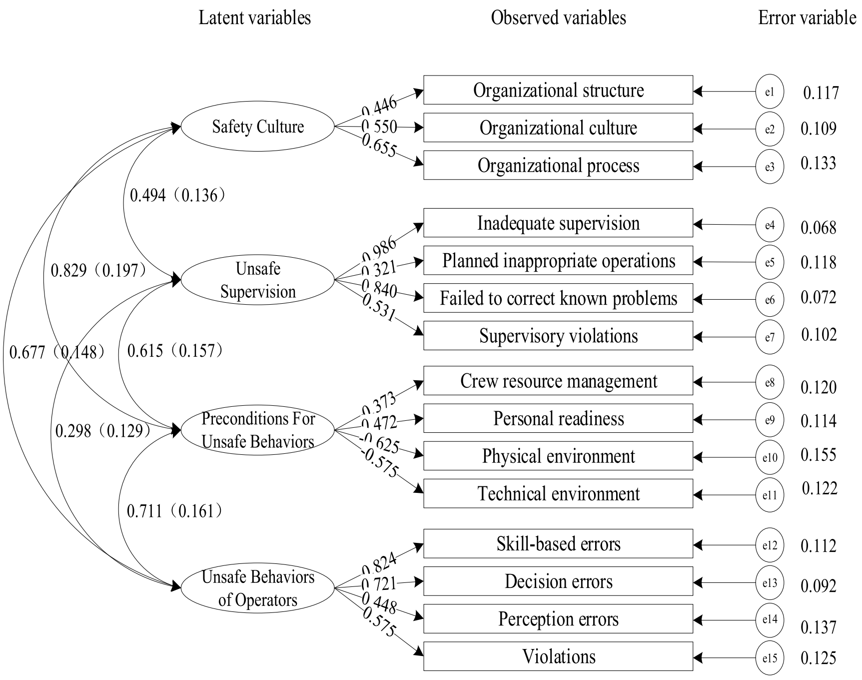

Fig. 3. Human error path of LOER incident in nuclear power plant.

levels. The results of this paper show that the Tau-y correlation measurement method and the chi-square test measurement method are basically consistent with the conduction path at the significance level $\alpha = 0.05$. Therefore, the path obtained by the Tau-y correlation measurement method is not described separately in Fig. 4. The fourth level of "organizational process" has a significant correlation with the third level of "inadequate supervision" and "failed to correct known problems". Organizational process mainly includes loopholes in the rules and regulations of nuclear power plants. When the rules and regulations of the organization cannot properly restrain the behavior of supervisors, it is easy to produce inadequate supervision and ineffective correction. Inadequate supervision, failed to correct known problems, and supervisory violations in the third level is significantly related to the physical environment and technical environment. The supervision of the managers of the third-level department is not in place, so that the defects in the technical environment and the physical environment are in a long-term failure, and become hidden dangers of the occurrence of events, examples are equipment failure and design problems in the technical environment cannot be found and corrected in time, and the space and light in the physical environment that do not conform to the human factor design have not been corrected in time. Ultimately, these hidden dangers combine with the unsafe behaviors of personnel to produce incidents. In addition, planned inappropriate operations at the third level have a significant correlation with crew resource management at the second level, which is manifested as improper planning and arrangement, so that the internal communication and coordination of the team are not in place. Supervisory violations at the third level are significantly correlated with personal readiness at the second level, possibly because the lack of oversight can easily reduce employees' skills and knowledge and job readiness. The status of the second-level crew resource management has a significant correlation with the skill-based errors, decision errors and violations in the first level. The most likely reason is that poor information communication and insufficient training within the team will directly lead to personnel errors and violations, and indirectly lead to the occurrence of incidents. The second-level technical environment has a significant correlation with skill-based errors and violations, and unreasonable design can easily lead to personnel violations and mistakes. Combined with Table 7, the analysis yields significant correlation paths from the fourth level to the first level of events is organizational processes →inadequate supervision → technical environment→ skill-based errors. This path is basically the same as the critical path obtained in the previous section. The difference is that the upper part of the third level is the physical environment. The physical environment does not have a direct significant correlation to the next level, so the technical environment with a large significant correlation at the same level is selected. The path does not conflict with the previous part of the path, and the two paths are more consistent.

5. Discussion and conclusion

The impact of weak safety culture on unsafe behaviors is a complex process in nuclear power plants. Latent errors play a

Table 7
Lambda correlation coefficient and Tau-y correlation coefficient among index factors.

	Chi-square test values	λy(x-y)	λy(y-x)	Tau-y(x-y)	Tau-y(y-x)
A1-A2	4.213	0	0	0.031	0.031
A1-A3	4.795	0	0	0.036	0.036
A1-C2	4.353	0.019	0	0.032	0.032
A1-D1	4.024	0	0	0.03	0.03
A1-D2	4.179	0	0.038	0.031	0.031
A2-A3	5.676	0	0.034	0.042	0.042
A2-C2	5.228	0.056	0	0.039	0.039
A2-D1	6.908	0	0	0.051	0.051
A2-D2	7.834	0	0.043	0.058	0.058
A3-B1	7.175	0.224	0.119	0.053	0.053
A3-B3	7.175	0.224	0.119	0.053	0.053
A3-C2	11.561	0.074	0.153	0.086	0.086
A3-C3	7.536	0	0.153	0.056	0.056
A3-D1	6.046	0.055	0.119	0.045	0.045
B1-B3	56.063	**0.642**	**0.642**	0.415	0.415
B1-B4	8.245	0	0.164	0.061	0.061
B1-C3	12.062	0	**0.224**	0.089	0.089
B1-C4	5.516	0.018	0.194	0.041	0.041
B1-D1	7.284	0	**0.224**	0.054	0.054
B2-C1	5.747	0.021	0	0.043	0.043
B2-C3	6.54	0	0.224	0.048	0.048
B4-C2	3.913	0.074	0	0.029	0.029
B4-C3	4.821	0	0	0.036	0.036
B4-D4	18.048	0	0	0.314	0.314
C1-D1	6.908	0	0	0.051	0.051
C1-D2	10.205	0.085	0	0.076	0.076
C1-D4	8.293	0	0.106	0.061	0.061
C3-C4	6.88	0.127	0	0.051	0.051
C4-D1	7.326	0.091	0.091	0.054	0.054
C4-D4	6.261	0	0	0.046	0.046
D1-D2	22.249	0	0.127	0.165	0.165
D2-D3	6.169	0	0.05	0.046	0.046
D2-D4	6.758	0	0.025	0.05	0.05
B3-C3	6.540	0	**0.164**	0.048	0.048

Note: The chi-square test and Tau-y values are significant in the table, and the lambda values in bold are significant values.

crucial role in this. Looking at the overall HFACS framework statistical results, active errors are mainly concentrated on the unsafe behaviors of operators at the sharp end of the organization, while latent errors are mainly concentrated in the last three higher organizational levels. The frequency of latent errors is 546 times, and the frequency of active errors is 159. The ratio of latent errors to active errors is about 3.4:1. Latent errors occur much more frequently than active errors. Arguably, latent errors pose the greatest threat to the security of complex systems [52]. The complexity and opacity of nuclear power plant systems facilitate the occurrence of latent errors. Eliminating latent errors at the blunt end of organization would bring greater benefits to complex systems.

From the results of structural equation model results, there is a many-to-many mapping correlation between the impact of safety culture on unsafe behaviors. There is a significant positive correlation between each level and the remaining three levels. The factor loading coefficient between the fourth level of safety culture and the third level of unsafe supervision is 0.494. The safety culture issue stems from decision makers at the blunt end of organization who set goals for the organization and allocate limited resources. Unsafe supervision corresponds to the managers of the sector, who execute the strategy of the decision maker within a specific area of operation. The consequences of wrong decisions (unreasonable formulation of rules and regulations, inadequate control measures, etc.) of middle and senior managers at the fourth level will affect inadequate supervision (unreasonable work arrangements, insufficient supervision and guidance). The implementation of departments may further aggravate the adverse impact of high-level decision-making, and even lead to bad effects of good decisions. The factor loading coefficient between the second-level preconditions for unsafe behaviors and the third-level unsafe supervision is 0.615, which has a high correlation relationship. At both levels, inadequate departmental oversight can be further man-

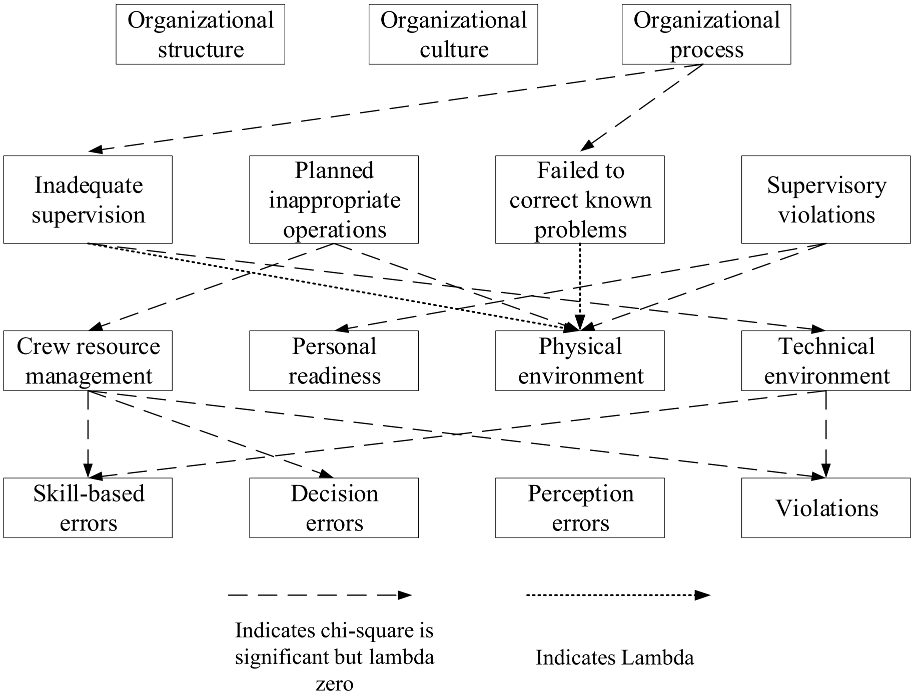

Fig. 4. Chi-square ($\chi2$) and lambda coefficients show a path analysis plot between significant adjacent levels.

ifested in a variety of prerequisites: inadequate work preparation, inadequate communication and understanding, and long-term equipment failures. Similarly, any one prerequisite (e.g., inadequate work preparation) may be the product of deficiencies in departmental management (e.g., poor work placement). The factor loading coefficient between the second level of preconditions for unsafe behaviors and unsafe behaviors is 0.711, which has a high correlation relationship. The preconditions for unsafe behaviors create the possibility of unsafe behaviors. Each precondition can lead to a large number of unsafe behaviors. Unsafe behaviors, in turn, will also promote the creation of preconditions for unsafe behaviors. For example, the violation of personnel makes the equipment unable to operate normally, further leading to the precondition for the next unsafe behaviors. Of course, the occurrence of first-level unsafe behaviors is not determined only by the previous level, but by the complex interaction between the first three levels. From the data analysis results, it can be seen that there is also a high correlation between unsafe behaviors and safety culture, with a factor loading coefficient of 0.677, and a low significant correlation between unsafe behaviors and unsafe supervision, with a factor loading coefficient of 0.298. This explains that in a nuclear power plant system, the same event usually involves multiple failures. When multiple latent errors occur at the same time as active errors, the danger can pass through layers of barriers and cause accidents or events. In addition, there is also a high significant correlation between safety culture and preconditions for unsafe behaviors. The factor loading coefficient reaches 0.829. It indicates that the lack of safety culture can directly bypass department managers, resulting in preconditions for unsafe behaviors, and then unsafe behaviors.

According to Chi-square test and the Lambda coefficient test, the critical path to the impact of nuclear power plant safety culture on unsafe behaviors is organizational structure→ inadequate supervision → physical/technical environment→ skill-based errors. This path is basically consistent with the four most important factors derived from the structural equation model. The results of the study are a good support for Reason's theory. Safety culture is embedded in the depths of the organization, closely related to the decision-making of the organization's senior management. Unclear decision-making is then transformed into inadequate supervision of the department (such as the imperfection of the procedural system, resulting in the lack of department supervision), resulting in the preconditions for unsafe behaviors (such as lack of skills and knowledge, poor state of equipment), which finally leads to unsafe behaviors of operators (such as skill-based errors, decision errors, etc.) and makes contributing to the occurrence of incidents. When there is a problem in the organizational structure within the organization, it is most often manifested as the lack of rules and regulations. It can easily lead to inadequate supervision of the department, which in turn leads to the failure of the environment and the skill-based errors of personnel, and then promote the occurrence of the events. Therefore, the rules and regulations formulated by the top level of the organization should be implemented from top to bottom within the organization. At the same time, sufficient attention should be paid to these four important factors.

Based on the above findings, it can be seen that the levels of the HFACS framework are closely related. The occurrence of a safety event is not caused by a single factor, but by a complex interaction between safety culture and unsafe behaviors. The occurrence of an event is determined by the complex interaction between the safety culture and the unsafe behaviors. Then the measures that can be taken are to eliminate the latent errors source of unsafe behaviors as much as possible on the basis of reducing unsafe behaviors. However, the elimination of latent errors is very difficult. This paper can only provide some suggestions for reducing the events rate of nuclear power plants based on the results of path analysis, starting from the factors that contribute the most to each level.

The most frequent occurrence in the hierarchy of unsafe behaviors is skill-based errors. To reduce the frequency of unsafe behaviors in nuclear power plants, we can improve crew resource management and the environment that can directly lead to skill-based errors, strengthen the training of operators, and keep the internal information flow more freely between different organizational layers. It is also necessary to pay attention to environmental factors, strengthen the maintenance of poor technical/physical environment, reduce equipment or environmental defects, and eliminate possible latent errors. Secondly, it needs to prevent the occurrence of unsafe behaviors that can be indirectly caused by supervision, and strengthen the risk awareness and training of supervisors. The highest level of the organization, safety culture, has a high correlation with preconditions for unsafe behaviors and unsafe behaviors. The relevant rules and regulations at this level have the greatest impact on the lower level. It can directly affect the regulatory deficiencies and failed to correct known problems of the next level, so the formulation of high-level decision-makers' systems and regulations needs to think twice. In summary, the impact of safety culture on unsafe behavior is the most profound and solid. Safety culture can indirectly affect unsafe behaviors through preconditions for unsafe behaviors and unsafe supervision. Therefore, to reduce the occurrence of unsafe behaviors, it is necessary to start from the root of the safety culture of nuclear power plants.

The purpose of this paper is to analyze how safety culture affects the unsafe behaviors of operators in Chinese nuclear power plants, using actual event data. However, it is important to acknowledge that identifying which factors in the research framework necessarily leads to or triggers an event is challenging from a practical perspective. Instead, our goal is to develop a methodology to investigate the potential impact of safety culture on unsafe behaviors and provide empirical evidence to support it. By doing so, we aim to offer power plants insights and guidance on how to enhance their safety culture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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