

# Application and Prospects of Human Error Safety Analysis in Nuclear Power

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**Abstract:** Based on the analysis of the scientific concept of human error and the developmental stages of human reliability analysis methods, combined with the current research status of human reliability analysis and human error safety analysis methods in nuclear power, this paper analyzes methods for human error safety analysis in nuclear power from the perspectives of personnel, organization, system, and accident analysis. It summarizes the existing shortcomings of current human error safety analysis methods in nuclear power from the perspectives of data, model, system, and application, and proposes the future development direction of human error safety analysis technology in nuclear power from the perspectives of data, model, system, and application. It is proposed that Class B human errors during the digital transformation of nuclear power should not be overlooked, and human error safety analysis methods should be applied to jointly optimize the digital transformation path of nuclear power, improve the analytical capability for Class B human error events, and reduce the safety risks caused by potential human errors during the digital transformation process.

**Keywords:** Nuclear power; Human error; Human reliability analysis; Safety analysis

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## 1. Introduction

To date, all nuclear accidents worldwide have been directly or indirectly related to human error. Research indicates that more than 60% of nuclear-related accidents worldwide are caused by “human error.” Developed countries such as the Republic of Korea, Germany, and the United States have strengthened the requirements for human error safety analysis in nuclear safety assessment and review. On 19 May 2021, the National Nuclear Safety Administration approved and released the Nuclear Safety Guide: The Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, which explicitly states that Level 1 PSA for internal events in nuclear power plants includes human reliability analysis.

Although human error is an important factor in the occurrence and escalation of nuclear power plant accidents, related accident and safety analyses are still mainly focused on technical failure analysis<sup>[1-8]</sup>.

With the advancement of artificial intelligence technologies and the digital transformation of nuclear power, increasing reliance on AI by personnel can lead to technology that influences human cognition, thus increasing the likelihood of human error. The coupling relationship between technical failures and human errors will also become increasingly tight.

To promote the application and development of human error safety analysis technology in nuclear power, based on the scientific concept of human error, this paper analyzes the current status of human error safety analysis technology in China’s nuclear power sector from the perspectives of human reliability and safety analysis. Combined with the digital transformation of nuclear power and the development trends of human error safety analysis technology, the paper also looks ahead to the future development and application of human error safety analysis in nuclear power, proposing that human factors engineering should be considered during the digital transformation of nuclear power and providing specific implementation methods or technical pathways for human error safety analysis in nuclear power.

## 2. Development of human error safety analysis methods

### 2.1. Development of the scientific concept of human error

The scientific concept of human error originated from psychological research. It is built on the material foundation of rapidly advancing technology and equipment, especially the extensive application of military technologies and equipment during World War II <sup>[9]</sup>. With technological progress and the widespread use of automated systems, the concept of human error science has gone through roughly three developmental stages, as detailed in **Table 1**.

Currently, in safety-related fields, human error is one of the leading causes of most accidents. In the transportation sector, according to a report from the National Highway Traffic Safety Administration in the United States, 94% of traffic accidents can be attributed to human error <sup>[5]</sup>. In aviation, human error is associated with the majority of aviation accident causes <sup>[6]</sup>. In healthcare, human error is the third leading cause of death in the United States <sup>[10]</sup>.

**Table 1.** Development stage of the concept of human error science

Stage	Time	Main characteristics	Representative figures
OriginStage	1900–1945	Psychological research	Freud Watson Bartlet Chapanis Fitts and Jones
Human factors	1945–1980S	human information processing and cognitive models	Payne and Altman Tversky Norman Wood and Hollnagel
System factors	1980S–now	cognitive systems engineering and resilience engineering	Suchman Hutchins Rasmussen

However, accident rates in many industries have plateaued, and the traditional perspective of human error and methods centered on human reliability are increasingly unable to meet the needs of industry

development <sup>[9]</sup>.

## 2.2. Development of human reliability analysis

With technological advancements and increasing equipment automation, a growing number of evolving concepts and human error phenomena have driven human reliability analysis and evaluation research, leading to the development of Human Reliability Analysis (HRA). HRA is a key research area in human factor engineering, focusing on analyzing, predicting, reducing, and preventing human errors <sup>[5]</sup>.

In 1964, Human Reliability Analysis (HRA) was formally introduced and initially applied to the quantitative assessment of human error impacts in a complex military system, roughly going through two stages, as shown in **Table 2**. The first generation of HRA emerged before 1990. During this period, many HRA methods were developed and applied, especially in the context of probabilistic safety assessment methods for nuclear reactor systems, which led to the creation of numerous HRA methods rooted in nuclear power applications. As the first generation of HRA evolved and was applied, doubts arose about the purely information-processing models of humans, prompting consideration of the context and cognitive decision-making processes in which personnel operate, ultimately leading to the emergence of the second generation of HRA methods.

**Table 2.** Stage of HRA development

Stage	Time	Main characteristics	Canonical method
First generation	1900–1980s	Human information processing and cognitive models	THERP ASEP AIPA HCR SLIM PC
Second generation	1980s to present	The context in which personnel are located and the cognitive decision-making process	HEART CREAM ATHEANA

It can be seen from the development stages of the scientific concept of human error that the development stages of HRA overlap with those of the scientific concept of human error. The evolution of two generations of HRA also reflects the shift of human error research from human factors toward systemic aspects. On the contrary, the development of the scientific concept of human error has provided a research foundation for HRA to overcome the limitations of human information processing models, enabling HRA to incorporate factors related to the context and cognitive decision-making in which personnel operate, and to advance toward the direction of cognitive systems engineering.

Although dozens or even hundreds of HRA methods have been researched and developed, data-related issues in these methods remain widespread, including data scarcity, difficulties in data organization and analysis, and the lack of standardized guidelines. Furthermore, research on the mechanisms of human error behavior still has shortcomings, particularly because human cognitive behavior is highly uncertain, leading to insufficient reliable validation of many theoretical studies, making it difficult to reproduce, analyze, and study through experiments.

## 2.3. Human error safety analysis

Human error safety analysis is based on a systems perspective and HRA. While HRA focuses on human factors, human error safety analysis emphasizes a systemic point of view. Since safety analysis encompasses

both deterministic and probabilistic methods, human error safety analysis also includes both deterministic and probabilistic analytical approaches.

The assumptions and design mitigation measures related to deterministic analysis of human error have been systematically covered by the safety design methodology, particularly the deterministic methodological outcomes from early human error and reliability research, which have been transformed into certain human factors engineering technical specifications and standards and applied in fields such as nuclear power. Probabilistic Safety Assessment (PSA) is an engineering safety evaluation method used to identify major risk factors in a system, estimate risks quantitatively, and compare various options for risk reduction. Human error is clearly one of the risk factors in the system. Therefore, applying PSA methods to evaluate human error can help identify key factors that contribute to human error, perform quantitative estimation, and optimize potential measures to reduce human error.

Evaluating human error safety risks using PSA methods requires HRA to provide technical support such as initiating event identification, accident sequence modeling, data evaluation and parameter estimation, and accident sequence quantification, and to be integrated into the overall PSA framework. The lower the effectiveness of HRA technology, the fewer events of human error it can analyze and predict, and the less meaningful the probabilistic analysis of human error.

### 3. Current status of human error safety analysis applications in nuclear power

#### 3.1. Human error and HRA in nuclear power

The International Atomic Energy Agency classifies human errors in nuclear power into three categories: Category A (human errors that occur before the initial event), Category B (human errors that trigger accidents), and Category C (human errors that lead to sequences of accidents or occur after an accident due to human factors). The Nuclear Safety Guide: Level 1 Probabilistic Safety Assessment for Nuclear Power Plants also categorizes human errors into types A, B, and C, consistent with the IAEA approach.

HRA is an indispensable foundation for the analysis and evaluation of human error safety in nuclear power. Quantitative analysis of Type A human error events typically employs classical HRA methods. Type B human error events are characterized by suddenness and unpredictability, combining features of both Type A and Type C events, and are extremely difficult to identify and predict, with very limited available data, so they are generally not subjected to separate quantitative analysis. Type C human error events have long been a focus of HRA quantitative analysis due to their severe accident consequences and the urgency of the accident response. **Table 3** summarizes the scenarios and typical HRA methods for the three types of human error events.

**Table 3.** Scenarios and HRA methods of 3 types of human error events

Type	Scenario	Canonical method
Category A	Human errors leading to safety systems or equipment being in a latent failure state under normal operating conditions Human error	THERP
Category B	Human error during operation tests or maintenance activities Due to the event itself or the subsequent failure of equipment Causing or leading to the initial event of an accident	STATISTICAL ANALYSIS
Category C	Human errors occurring during the interaction between humans and systems under abnormal system conditions Errors during interaction	RISK SIGNIFICANCE CUT SET

Among these three types of human error incidents, Type B incidents involve the operation (such as operation, testing, and maintenance) of nuclear power plants. Human errors during the work process lead to complex paths of potential equipment failures or system abnormalities, which are sudden and unpredictable, making their identification and analysis challenging. However, the consequences they cause are severe, and their contribution to the initial event cannot be ignored.

Currently, with the advancement of artificial intelligence technology, nuclear power is undergoing a digital transformation to achieve sustainable operation. With the widespread application of intelligent technologies and the change of operational models, intelligent technologies will lead to the redistribution of human-machine tasks (for example, intelligent inspection robots replacing manual inspections). The mutual influence between human error and the failure of intelligent technologies further increases the difficulty of analyzing Type B human errors. Since Type B human errors cannot be ignored in the operation of nuclear power and the digital transformation process, adequate attention must be paid, and reasonable scientific analysis and evaluation must be performed to determine appropriate preventive measures.

### **3.2. Current status of human error safety analysis method application in China's nuclear power**

The scientific concept of human error has evolved over the past century, yet definitions of human error incidents have remained inconsistent. This inconsistency is primarily due to differing views on the relationship between human error and unintended consequences — whether human error is a direct cause, root cause, or contributing factor — and whether unintended consequences must be final results. These differences have led to various levels of human safety analysis methods and application scenarios, including primarily the directions of personnel, organization, systems, and accident analysis.

To analyze and summarize the current status of research and application of human error safety analysis methods in China's nuclear power sector, keywords such as “nuclear power human error” and “human reliability analysis” were searched on the China National Knowledge Infrastructure (CNKI) platform. The final analytical literature was selected on the basis of the main content of the documents, and the analysis and summary were conducted accordingly.

Safety analysis methods focusing on human behavior are based on the study of human error mechanisms, including cognitive patterns, cognitive rules, and types of human errors. This article summarizes the relevant research in China on safety analysis methods centered on human behavior.

In summary, the existing safety analysis methods for human behavior focus mainly on operators. However, human behavior in other processes within nuclear power plants has received little attention, and intelligent decision-making systems and human error safety analysis methods have not yet been established.

Traditional Hazard and Operability Analysis (HRA) focuses mainly on human errors caused by individual factors and lacks a comprehensive assessment of organizational factors. Therefore, human error safety analysis methods in organizations have attracted great attention and research from many scholars. The table below summarizes the relevant research in China on safety analysis methods centered on organizational factors.

Although research on organizational factors has made personnel error safety analysis more comprehensive, existing research on organizational factors is still unable to systematically analyze the large number of coupled organizational factors in the complex operation of nuclear power plants. The coupling

transmission process and mechanism of influence among organizational factors remain underresearched, and most studies are limited to organizational behavior and control room operator crews.

From the perspective of the expected consequences of human error, methods for analyzing human error safety have emerged from the points of view of systems or accidents. From a system perspective, human error safety analysis must consider the interaction between people (including organizations) and the technical system. From the perspective of expected consequences, human error safety analysis needs to consider the impact of human errors on accident outcomes.

This includes human errors and their impact on the consequences of accidents under accident conditions — commonly referred to as Class C human error accidents. The following table summarizes relevant research in China based on safety analysis methods for systems and accidents.

Currently, human error safety analysis at the system and accident levels mainly focuses on human-machine interface interactions in the main control room and operator behavior following specific accidents. However, it has not yet considered the coupling of social, organizational, technical, and procedural factors from a broader sociotechnical systems perspective, nor has it addressed human errors in other work processes or the accident mechanisms caused by human errors.

#### **4. Limitations and prospects of human error safety analysis methods in nuclear power**

Although research on human error safety analysis methods in nuclear power has yielded abundant achievements and practical experience, many human factor analysis methods remain limited to control room personnel and organizational behavior. Furthermore, due to the high uncertainty in human cognitive behavior and organizational factors, much theoretical research lacks sufficient and reliable validation, making it difficult to analyze and study through experiments. Nuclear power plant operation involves not only control room operators but also other work processes such as equipment maintenance and configuration management. Human errors must be considered comprehensively in terms of social, technical, procedural, personnel, and organizational factors. This complexity leads to intricate relationships between human errors and accidents in nuclear power, with diverse pathways between expected and actual consequences, resulting in various research approaches and methodological systems for human error safety analysis, making the analysis of human error in nuclear power exceptionally complex.

From the perspective of sociotechnical systems theory, existing human error safety analysis methods have not fully considered integrated analysis and optimization between personnel, technology, processes, and management, and have even overlooked the impact of socio-environmental factors on personnel, organizations, and management. Especially under unprecedented global changes, advances in information technology, climate change, social aging, pandemics, natural disasters, and regional conflicts all influence the operational organizational models and human cognitive models in nuclear power, thereby affecting the long-term safe operation of nuclear facilities.

The research focuses on the future safety analysis of human error in nuclear power, including mainly the following aspects:

- (1) By adopting intelligent inspection methods (such as intelligent inspection robots or RPA process automation robots), standardized data collection and test verification methods are established to improve data quality and provide reliable data sources for quantitative safety analysis.

- (2) Utilizing advanced cognitive theories to enrich and improve existing cognitive-based human reliability analysis methods can improve the generalizability and accuracy of HRA models.
- (3) Establish a unified theoretical framework based on socio-technical system theory and enable existing methods to be unified and jointly optimized within the framework of socio-technical system theory.
- (4) Combining appropriate methods for specific application scenarios can quickly develop effective human safety analysis methods, and establishing a system for the joint optimization of multiple methods is a key direction for promoting the rapid application and theoretical progress of human error safety analysis methods.

In addition, most human error safety analysis methods are primarily based on modeling and mechanism research, requiring people with strong professional expertise to perform such analyses. With the advancement of big data and artificial intelligence technologies, the use of data-driven approaches to study human errors and HRA has become an important direction. In particular, numerous intelligent inspection methods (such as intelligent inspection robots and smart monitoring systems) not only reduce human and organizational error factors but also improve the standardization and quality of data collection. By employing data-driven methods, analysis models can be continuously iterated and optimized using data, enabling rapid human error safety analysis and the establishment of a dynamic and intelligent decision-making system for human error safety analysis.

Although the digital transformation of nuclear power will accelerate the application of data-driven methods in human error safety analysis, the changes in work processes brought about by the digital transformation will increase the difficulty of analyzing Class B human error events. Given the serious consequences of Class B human error events, the event cannot be overlooked. Therefore, during the digital transformation of nuclear power, human factor engineering should be considered, and human error safety analysis methods should be applied to jointly optimize the digital transformation path, enhancing the ability to analyze Class B human error events and reducing the safety risks posed by potential human errors during the digital transformation process.

## 5. Conclusions

Based on the analysis of the scientific concept formation process of human error and the development of HRA methods, combined with the current research status of human error safety analysis methods in nuclear power, this paper analyzes existing human error safety analysis methods in nuclear power from the perspectives of personnel, organization, systems, and accident analysis. It summarizes the shortcomings of current human error safety analysis methods in nuclear power and looks forward to future development directions in terms of data, models, systems, and applications. It proposes that B-class human errors during the digital transformation of nuclear power should not be overlooked and that human error safety analysis methods should be applied to jointly optimize the digital transformation path of nuclear power, improve the ability to analyze B-class human error incidents, and reduce safety risks caused by potential human errors during the digital transformation process.

## Disclosure statement

The authors declare no conflict of interest.

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