Human Errors in Nuclear Management: Causes, Consequences, and Preventive Measures

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Abstract. The use of nuclear technology has been one of the most significant advancements in human history, providing both immense energy potential and devastating military power. While nuclear energy has offered cleaner alternatives to fossil fuels, it also comes with risks, primarily due to human errors in handling nuclear materials and facilities. These errors can lead to catastrophic consequences, as seen in major nuclear accidents throughout history. By reviewing current literatures, this article is aimed to identify the benefits and risks of nuclear, the causes of human errors, several preventive measures, and nuclear policy and cooperations within ASEAN. The findings reveal that human errors in nuclear operations stem from a variety of factors, including lacking proper training and expertise, poor communication and misinterpretation, fatigue and stress, overconfidence and complacency, deficiencies in safety culture and regulations, and extremism. Further, Southeast Asian nations are increasingly considering nuclear power as a solution to meet growing energy demands while addressing climate change concerns. ASEAN is advised to implement comprehensive energy legislation that emphasizes sustainability, addresses technical and budgetary limitations, and promotes public awareness. Experts recommend expanding regional cooperation frameworks, which encompass the fortification of capacity building, the establishment of networks of nuclear security centers, and the enhancement of emergency readiness. This study may help academics and practitioners in understanding human errors in nuclear management.

Keywords: Nuclear Management, Human Errors, Safety Culture.

1 Introduction

Nuclear technology has a significant development in human history, providing both energy potential and military power. Nuclear power provides a cleaner alternative to fossil fuel, but it comes with risks mostly due to human errors in handling nuclear materials and facilities [1]. These mistakes can be fatal, as demonstrated by major nuclear accidents throughout history. The transition from conventional nuclear operations to advanced technology has sometimes led to unintentional human errors, resulting in power plant shutdowns and unnecessary costs [1]. To mitigate these risks, artificial in-

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telligence has been integrated into operational support systems, including decision support, sensor fault detection, and safety assessment systems [2]. Despite extensive political and institutional mechanisms regulating its use, nuclear energy continues to pose risks that many consider unacceptable, leading to ongoing debates about its safety and social impact [3].

Human errors in nuclear facilities remains an important issue since study shows higher rates of omission errors than previously estimated [4]. Although the increasing implementation of advanced technology in nuclear operation has its benefits, it also has led to new problems and potential aggravation of human errors [1]. To alleviate this risk, artificial intelligence (AI) technology is integrated into various operator support systems, including decision support, sensor fault detection and operator monitoring system [2]. But especially when dealing with nuclear weapons, human elements are crucial. It is an important preventive measure to guarantee the stability and reliability of manpower in charge of nuclear weapons and to maintain effective security due to unauthorized use [5]. As nuclear technology continues to develop, assessing human performance and human factors in system design is still important to maintain security and prevent nuclear facilities accidents.

The use of nuclear technology for power generation has long been promoted as a clean and efficient alternative to fossil fuels. Proponents highlight its ability to produce large-scale, low-carbon electricity, which is crucial in combating climate change. However, concerns over safety—especially those related to human factors, including human errors—have fueled ongoing debates about whether nuclear energy is truly safe for society. In nuclear facilities, "human factors" refer to the interaction between people, technology, and organizational systems. While nuclear reactors are designed with multiple safety layers, their operation ultimately depends on human decisions and actions. Nuclear power safety remains a contentious issue. Proponents argue that modern plants have sophisticated safety mechanisms and decades of safe operation, with risks lower than fossil fuels [6]. However, statistical analysis suggests nuclear accidents may be more frequent than expected, with a core-melt accident rate of 1 per 3704 reactor years [7]. The historical record of nuclear incidents raises concerns about disaster probability [8]. Human factors play a crucial role in nuclear safety, with research focusing on safety culture, human error, and human-machine interaction [9]. While traditional methods like probabilistic risk assessment persist, newer approaches such as resilience engineering are emerging [9]. Despite safety improvements following major accidents like Chernobyl and Fukushima [6], the debate continues on whether nuclear power can be operated without major accidents [7]. The issue is highlighted in this paper. By means of review of present literatures, this paper aims to explore the good and bad of nuclear, the definition and sources of human errors, numerous repercussions of human errors in nuclear management, and some preventive actions. This study could clarify human mistakes in nuclear management for professionals and scholars.

2 The Dual Face of Nuclear Power

2.1 The Benefits of Nuclear Energy

Nuclear energy provides a potential advantage that can mitigate climate change, but the implementation is faced with serious problems. Despite the fact that it provides an alternative to fossil fuels [10], the debate over nuclear energy is often focused on values than empirical problems [11]. Some argue that nuclear weapons are a force for peace and increase national security at a reasonable cost [12]. Nevertheless, the risks related to nuclear escalation and terrorism are particularly important in the context of global expansion [13]. The next 10 years is important for establishing appropriate technologies and control standards to ensure sustainable contributions of nuclear power to climate change mitigation [13]. Ultimately, the controversy related to nuclear power include complex trade-offs between economic and technological advantages and perceived psychological risks [11], which make it a multifaceted issue with impacted lifestyle, politics and international relations.

2.2 The Risks of Nuclear Energy

Nuclear energy has been praised and criticized as a potential advantage and dangers. Some argue that nuclear weapons contribute to peace and safety [12], but others highlight the dangers related to nuclear power plants and its radioactive waste [14–16]. Nuclear energy is considered a low-carbon option to secure global energy and to mitigate climate changes [14]. Regardless, concerns stay in nuclear accidents, management of radioactive waste and environmental contamination [14–16]. The biological effects of ionized radiation, includes genetic mutations and cancer possess a significant risk [15]. Critics argue that the risk of nuclear energy surpass its benefits by mentioning problems such as uranium mining, the safety of reactors and long-term waste storage [15, 16]. Alternative energy sources, such as solar and fusion powers, are proposed as a safer option for future energy production [15].

3 Methods

This study applied literature review to to gather data on human errors in nuclear management. A literature review is a methodical process of discovering, assessing, and integrating existing research pertinent to a certain subject, in this instance, the advantages and disadvantages of nuclear energy, as well as human errors in nuclear management. The literature review process functions as a foundation and justification for the study, ensuring that this study is guided by existing knowledge and scholarly debates. The literature review of this study seeks to delineate the current state of knowledge, highlight theoretical and methodological trends, identify gaps in the existing research, and situate this study within an academic framework. By rigorously analyzing prior research, the authors of this study build upon established findings. This study's literature review technique comprised the subsequent steps: 1) delineating the scope, which pertains to human errors in nuclear management, 2) implementing search strategy, which was on Scopus, Web of Science, PubMed, or Google Scholar, to identify relevant sources, 3) selecting and screening sources based on their relevance and credibility, 4) identifying key concepts, patterns, contradictions, and research gaps, 5) critically evaluating each source's strengths and limitations, 6) organizing the findings, by starting with broad themes and narrowing to specific studies.

4 Results and Discussion

Human errors are an important issue in various fields, especially industrial and engineering operation. They range from minor to fatal accidents [17]. Rasmussen (1982) proposed a classification of human error taxonomy with consideration of various types of behavior and error mechanisms [18]. Dhillon (1989) studied the causes, the consequences and the prevention methods of human errors, emphasizing the importance of data banks on human reliability [19]. Zhang et al. (2000) presented a cognitive theory of slips and categorizing them into caption, description, associative activation, and loss-of-activation slips [20]. This theory aims to explain and predict when slips happen, and provide the foundation for designing system that minimize human errors. It is important to understand the nature of human errors to development effective strategies to reduce its occurrence and its effect in various conditions from industrial installation to computer systems [18–20].

4.1 Human Errors

Human error is a complex concept that is widely studied in various industries. In general, it is defined as a failure of a planned action to achieve the desired results [21]. Rasmussen (1982, 1987) argues that human errors are not an objective event, but rather situations where a person's actions don't match the task that need detailed instruction properly [18, 22]. He provides classification for analyzing human malfunctions and designs error-tolerant systems. To identify whether something is a human error depends on the rules used to analyze and explanation of what happened after the event already occurred [22]. Gray et al. (1993) reviewing Rasmussen's work, highlighting its strength to clearly define different types of errors and argues that errors is result of normal cognitive processes [23]. Understanding human errors is important to increase the safety and efficiency in industrial setting, and it requires careful studies on actual work situation to better characterize these complex phenomena [18].

4.2 Types of Human Errors

Human errors are a serious concern in various fields, especially health care and aviation. They can be widely classified as active and latent errors [24, 25]. While active errors occur immediately before an incident, hidden errors are system defects that apparent in specific situations [25]. In aviation, errors are classified as slips, lapses and mistakes, with lapses and mistakes are more difficult to detect and often require external intervention [26].). Workers averagely have one error in each 1000-10,000 actions, but many jobs have thousands of actions per day, so the prevalence of the error can be misleading [25]. In order to address human error, it is very important to understand the cause and implement preventive strategies [24]. The approach of the aviation industry to error management focusing on understanding causality rather than blame, can be adapted to other fields like healthcare [25, 27].

4.3 Causes of Human Errors in Nuclear Handling

Human errors remain an important cause of the incidents on nuclear power plants, with various factors contribute to these errors. Lack of theoretical knowledge, poor manipulation and organizational management failure are identified as the main cause [28]. Maintenance activities especially during refueling outages and plant modification are vulnerable subject to human errors and can lead to dependent failure [29]. The Korean Human Performance Enhancement System (K-HPES) is implemented to reduce human performance errors through follow-up measures like facility inspection, procedure revision and staff training [30]. As the operator becomes more familiar with the computer control system, knowledge and rule-based mistakes reduced, while slip and lapse errors persist [31]. These findings emphasize the importance of proper training, effective communication and stable safety culture in mitigating human errors in nuclear handling operation.

4.4 Human errors in nuclear operations stem from a variety of factors

Lack of Proper Training and Expertise. Processing of nuclear materials and operating nuclear power plants requires expertise and extensive training. However, human mistakes can occur when employees lack proper education, understanding or experience. Errors in handling nuclear reactors, fail to follow the safety protocol or a miscalculation during the processing of radioactive materials, can cause serious accidents. Research emphasizes the importance of human expertise in the operation of advanced systems, especially without proper training. In many fields, the system often is beyond operators' capabilities and leads to errors especially when proper training is not provided [32]. The development of expertise really depends mainly on domain-specific knowledge and anticipation skills [33]. Nevertheless, management training often ignores human aspects and creates "idiot savants" who are skilled in solving social and economic challenges but lack in understanding [34].To solve this problem, the training curriculum must focus on the knowledge and skills that is crucial for expert work [33]. Moreover, the expertise acquisition includes the conceptualization of experience in a way that is similar to human operators [35]. Integrating human aspects and social sciences into training in various fields is important for effective solutions for system problem and operation.

Poor Communication and Misinterpretation. Clear communication is important in nuclear facilities. Misunderstandings between operators, engineers and supervisors can lead to incorrect actions. For example, if an operator of reactor misinterpret a warning signal and fails to communicate an emergency correctly, it can develop into disaster. Bad communication can result in serious consequences, even cause a casualty [36, 37]. Research shows that communication often goes through self-centeredness, speakers overestimate their capability and interpret messages from their own perspective, thus contribute to systematic misinterpretation [38]. Communication malfunctions in many areas are complex and include hierarchical differences, ambiguity of role, and interpersonal conflict [37]. These issues can lead to dangerous misunderstandings [36]. It is important to improve communication skills among professionals to prevent side effects and increase safety [37, 39]. The solution to these communication issues requires intervention of organizational practices to foster clearer and more effective interactions between employees [37].

Fatigue and Stress. Workers at nuclear plant often work in long shifts under stressful conditions. Fatigue can exacerbate decision making, slow reactions, and increase the possibility of errors. Stress can lead to panic responses, which makes the situation worse. Human fatigue and stress is huge concerns in various occupational setting. It affects efficiency, safety and health consequences [40, 41]. These conditions are the result of the complex interaction between the individual (internal) difference and the characteristics of the task, which leads to exhaustion and puts extra strain on the body's coping systems [42]. Physiological signals such as ECG and EMG can be used to measure fatigue and stress levels [40]. The visual and decision-making fatigue is particularly problematic in many areas, which potentially can cause wrong diagnosis and inefficient work processes [43]. Factors that contribute to professional stress and fatigue include excessive workload, sleep deprivation and technical use [41, 43]. To solve this problem, objective collection and analysis of data is important in consideration of the dynamic characteristics and individual volatility of stress and fatigue [43]. Understanding these factors is important to develop effective strategy to ease their impact on performance and safety.

Overconfidence and Complacency. Experienced operators can be overly confident with their skills and underestimate the risk involved. Complacency in security measures, ignoring minor warnings or skipping a daily inspection can contribute to serious errors over time. Excessive trust in automation systems (automation complacency), can reduce alertness and performance problems of human and machine/equipment interactions [44, 45]. This phenomenon takes place in various tasks condition and affects beginners and experts, despite trainings or instructions [45]. Complacency are related to individual differences, including self-efficacy and stimulation levels [46]. In many fields, complacency is a controversial concept used in accident investigation and legal process [47]. However, the legitimacy in this context is still questionable due to conceptual confusion, uncertain evidence, lack of valid measures, limited external validity of short-term experiments and lack of effective intervention [47]. The integrated model suggests that complacency is caused by the interaction of individuals, situations and factors related to automation, where attention playing a central role [45].

Deficiencies in Safety Culture and Regulations. Some nuclear facilities are suffering from a weak safety culture that employees are not encouraged to report safety issues. In some cases, regulators may fail to enforce strict rules/guidelines, enable unsafe practices persist. This was evident in several nuclear accidents when the operator ignored the warning signal caused by institutional failures. Safety culture of regulators and industries is important for preventing accidents and increasing general safety. The lack of regulatory supervision is identified in various areas, emphasizes the necessity of regulatory body to develop positive safety culture [48]. Process safety assessment can help identify and fix the lack of organizational safety culture [49]. Nevertheless, some argue that regulators should focus on rules and safety management systems, not dictating cultural norms [50]. Developing valid and reliable tools to assess regulatory safety culture is crucial [48] to support the prevention of accidents [51]. Ultimately, to eliminate the deficiencies of safety culture, a multifaceted approach involving regulators and industries is required.

Extremism. Logical fallacy and misconceptions of ideological concepts and philosophical teachings are forms of hazardous human errors if we view humans as "Super AI". In other words, as ideology/religions is "an equipment" for humans to reach wisdom, extremism in the mind of personnel who handle nuclear technology is certainly considered as human error. Extremism is a complex phenomenon that has been studied from various perspectives. Schindler (2022) provides a philosophical analysis of the concept [52], while Schmid (2013) explores the related terms of radicalisation, de-radicalisation, and counter-radicalisation [53]. Furthermore, Michael (2013) offers a comprehensive overview of different forms of extremism, ranging from far-left to far-right ideologies, (i.e., anarchism and black nationalism) [54]. He notes that while some extremist groups face repression, others enjoy a degree of respectability in mainstream society. The relationship between extremist movements and the larger society is examined, along with recent trends in political extremism [54]. These studies collectively highlight the diverse manifestations of extremism and its impact on politics and society, emphasizing the need for continued research and understanding of this phenomenon.

4.5 Notable Nuclear Accidents Caused by Human Error

Nuclear accidents are often attributed to human errors, but deeper analysis shows the complex interaction of several factors. The mistake of the operator can contribute to voluntary disasters such as Chernobyl, Three Mile Island and Fukushima but those generally result of a combination of technological, organizational, and human factors [55]. The implementation of advanced technology in nuclear institutions although beneficial, if it is not properly managed, it can potentially exacerbate human errors issues [1]. For example, Chernobyl is better understood as a system accident, not a human error, including an improbable and unpredictable event [56]. In order to prevent such accident, it is important to consider human factors in the system design, improve training, and increase organizational responsiveness [55]. In addition, the decision to address environmental distractions, the reliability and procedural issues of the equipment is important for maintaining nuclear criticality safety [57].

4.6 Consequences of Human Errors in Nuclear Handling

Human errors in nuclear handling can have significant consequences, requiring advanced technology and system to reduce risk. Implementation of new technologies in nuclear facilities can unintentionally lead to accident due to human errors, resulting in plants shutdowns and environmental impacts [1]. To solve this problem, the advanced Man-Machine Interface Systems (MMIS) are developed to prevent and mitigate human errors, incorporating automation, operator support systems, and computer-based procedures [58]. The nuclear industry recognized the importance of human factor in safety, the development of methods human performance in complex system [59]. Artificial intelligence (AI) is increasingly used to detect and mitigate human factor errors in nuclear power plants through various operating support systems, including decision support, sensor fault detection and autonomous control system [2]. These advancements aim to improve the overall safety and efficiency of performance of nuclear facilities.

4.7 A The Madman Theory

The handling of nuclear energy has high risks due to the unreliability and potential instability among humans in control. This theory emphasized the fear of thousands of unstable people who participated in nuclear weapons management [5]. The assumption that nuclear-armed leaders will always act rationally is fundamentally wrong and dangerous, according to Ogilvie-White (2021) [60]. The US president's unchecked authority to order nuclear attacks combine with unstable nuclear posture unfortunately may cause existential risks [61]. To mitigate this risk, experts suggest to remove first use and launch on warning options, the reconstruction of the nuclear command chain, and building a reliable nuclear command system [61]. Mental and emotional loads for those in charge of nuclear weapons are important, and mental stability that is crucial during the crisis is often overlooked [5]. These factors emphasize the importance of effective protection and stability measurement in nuclear weapons handling to prevent random or inadvertent nuclear war [5].

The "Madman Theory," originally associated with Richard Nixon, suggests that leaders can gain coercive advantages by cultivating an image of irrationality or instability [62, 63]. This theory argues that unpredictability of leaders may enhance the threats [62]. Historically, Nixon used this tactic in the Vietnam War to order a secret nuclear alert in October 1969 to express his willingness to take extreme measures [63]. Other historical examples of leaders associated with the Madman Theory include Hitler, Khrushchev, Hussein, and Gaddafi [64]. Modern wars have been transmitted to the sides of the biopolitical and global governance, but the nuclear infrastructure of the Cold War remains a big concern [65]. The nuclear strategy to face "crazy man" has been revived recently especially in the context of Russian's invasion to Ukraine and Vladimir Putin's nuclear rhetoric [62]. However, empirical research challenges the theory's effectiveness.

McManus (2019) identified four types of perceived madness in coercive bargaining, arguing that situational extreme preferences are most advantageous [66]; yet, large-scale empirical analysis suggests that perceived madness can be detrimental to general deterrence and sometimes harmful in crisis bargaining, potentially due to commitment problems [64]. Schwartz (2023) found limited support for the Madman Theory in international coercion but highlighted significant domestic costs that may undermine its effectiveness [67]. The application of prospect theory to coercive bargaining reveals that different types of reference points, such as power-based, equity, status quo variants, and extreme "I-want-it-all" positions, can produce varied bargaining behaviors and outcomes [68]. These findings collectively suggest that while perceived madness may offer some advantages in specific coercive scenarios, its overall effectiveness is limited and potentially counterproductive in both international and domestic contexts.

4.8 Lessons Learned and Preventive Measures

Major disasters caused by human errors in nuclear technology prompt increased interest in human factors and safety culture in nuclear industry. The accident at Three Mile Islands and Chernobyl highlighted an important role in the non-technical side in atomic safety [69]. These events have caused the improvement of safety measures, regulation and technology [9]. The nuclear industry traditionally focuses on topics such as safety culture, human error and human-machine interaction with the emergence of new concepts such as resilience engineering [9]. Lessons learned from past accidents were important for the development of nuclear security attributes [70]. In order to improve nuclear safety, an integrated approach that combines the understanding and understanding of organizational and personal performance indicators and safety culture insight [69]. International cooperation is important for improving safety culture and address human and organizational factors in nuclear power plants around the world [71].

In radiation protection, lesson learned (LL) obtained from accidents are important for enhancing safety measures and nuclear knowledge management [72]. The study of human error prevention of nuclear power plants focused on the development of complex strategies and technology. Short-term measures include strengthening employee management, improving workplace environment and improving human factors regulation [73]. Long-term approaches include studies on human aspects such as fitness for duties, job competence, communication and teamwork [31]. The Korean Human Performance Enhance system (K-HPES) has been implementing to analyze and prevent human errors using follow-up measures such as facility inspections, procedure revisions, and employee training [30]. The recent advancements in the intelligent technology lead to AI-assisted devices that provides intelligent supervision and reminders to operators, reduce cognitive loads and prevent errors in rule-based tasks [74]. This combined effort aims to improve the work efficiency, human reliability and overall safety of nuclear power plants operations.

4.9 Nuclear Energy in Southeast Asia's Future

Southeast Asian countries are increasingly considering nuclear power as a solution to meet growing energy demands while addressing climate change concerns [75, 76]. Small modular reactors (SMRs) are emerging as a strategic option for the region, offering potential benefits for energy security and economic development [77]. As countries like the Philippines, Indonesia, and Thailand consider nuclear energy projects, competition among potential nuclear vendors such as China, Russia, South Korea, and Japan is intensifying, with significant strategic and economic implications for the region [78].

While current intentions appear peaceful, there are challenges/concerns about potential future risks [79]. Successful implementation, seen by many experts, requires addressing critical issues such as regulatory frameworks, human resource development, and waste management [76]. The Association of Southeast Asian Nations (ASEAN), in this case, play a crucial role in developing a regional normative framework for nuclear safety and security [75, 76].

ASEAN leaders have promoted civilian nuclear power while emphasizing the need for a regional nuclear safety regime [80]. To ensure safe and sustainable nuclear energy development, ASEAN is recommended to adopt comprehensive energy laws focusing on sustainability, technical and financial constraints, and public awareness [81]. Experts recommend expanding regional cooperation frameworks, including strengthening capacity building, establishing networks of nuclear security centers, and enhancing emergency preparedness [82]. Global non-proliferation instruments, such as UN Resolution 1540, have been implemented, but their effectiveness is limited by perceptions of West-centric agendas and insensitivity to local contexts [83]. Southeast Asia's regional security frameworks, such as the Asia-Pacific Economic Cooperation (APEC), the ASEAN Regional Forum (ARF), and the ASEAN Senior Officials Meeting on Transnational Crime (ASTOP) have had mixed success in promoting compliance with global instruments. Bilateral arrangements and focused multilateral discussions have been more effective in fostering trust and cooperation. Creating a "proliferation firewall" around Southeast Asia, combining global support with regional multilateral arrangements, is suggested to minimize risks [79]. The ASEAN Network of Regulatory Bodies on Atomic Energy (ASEANTOM) also plays a crucial role in fostering regional cooperation on nuclear safety and security, particularly benefiting countries like the Philippines in their nuclear energy preparations [84].

Malaysia, one of ASEAN member states, has been exploring nuclear energy as a potential solution to its energy challenges, including depleting domestic gas supply and overdependence on fossil fuels [85]. The country has taken steps towards implementing nuclear power, such as establishing the Nuclear Power Corporation of Malaysia and formulating a National Nuclear Policy [86]. Regulatory requirements for nuclear power plant site selection have been developed, aligning with es like the International Atomic Energy Agency (IAEA) and the US Nuclear Regulatory Commission (USNRC) guidelines [87]. Nonetheless, Malaysia faces several challenges in deploying nuclear energy, including the need for collaboration with nuclear-resource-rich countries, compliance with IAEA requirements, and the introduction of relevant legislation and policies [88]. Public acceptance is crucial for the implementation of nuclear energy, and surveys have been conducted to gauge Malaysian public perception [86]. The development of nuclear power in Malaysia aims to address energy security, sustainability, and contribute to achieving Sustainable Development Goals/SDGs [88].

Another case study of ASEAN member states is Vietnam. Vietnam has been exploring nuclear energy development to meet its growing power demands and reduce reliance on fossil fuels [89, 90]. Despite not possessing nuclear weapons or power plants, Vietnam has actively adopted nuclear security measures as a preventive step against nuclear terrorism [91]. The country has engaged in nuclear cooperation with the United States, strengthening bilateral ties in various sectors [92]. However, Vietnam faces challenges in implementing its nuclear program, including concerns about safety, regulatory mechanisms, waste management, and proliferation risks [90]. The location of nuclear plants, particularly in tsunami-prone areas like Ninh Thuan province, raises additional safety concerns [89]. Furthermore, establishing a robust nuclear management system with high safety standards in a short timeframe presents significant difficulties for Vietnam [89].

5 Conclusions

Nuclear technology invention is one of the most important achievements in history. It gives massive energy potential and also destructive military power. Even though nuclear power provides cleaner alternative to fossil fuels, there is a risk from human errors in processing its nuclear materials and nuclear facilities.

Human errors are a major concern in nuclear management. The improvement in technology, such as artificial intelligence and automation, in improving detection and mitigation creates new challenges that need careful supervision. Nuclear accidents that happened in the past showed devastating consequences when human reliability, organizational culture, and technological measures are not aligned properly.

A comprehensive approach is needed to solve this human error issue. Strict and proper training, strong regulatory frameworks, and a proactive safety culture are among the needed approaches. Implementing a human performance development system, improving operational procedures, and promoting international cooperation should be done to minimize risks, along with constant adaptation and improvement of nuclear safety protocols.

Incorporating human factors into the continuously developing nuclear system design is important. A balance is needed between human supervision and technology innovation. Besides being a technical necessity, it is also a moral responsibility. The risk of the nuclear industry can be reduced by fostering a culture of responsibility and progress. The ability to prioritize safety, transparency, and education can cultivate public trust in nuclear energy.

ASEAN countries are increasingly interested in nuclear energy development, driven by energy security and climate change mitigation goals. Regional cooperation mechanisms like ASEANTOM play a crucial role in addressing nuclear safety, security, and emergency preparedness issues. These mechanisms can help countries like the Philippines address critical gaps in their nuclear energy preparations. However, ASEAN needs to strengthen its regional normative framework to promote nuclear safety and security. This includes developing comprehensive energy laws focusing on sustainability, technical and financial constraints, and public awareness. To enhance nuclear security in the broader Asia-Pacific region, ASEAN could pursue a regional action plan, strengthen capacity building, establish a network of nuclear security centers of excellence, and improve emergency preparedness and response. These efforts can contribute to a more robust collaborative framework for nuclear security in the region.

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