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Safety Management for Nuclear Plants

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Abstract

Safety Management in nuclear power plants is moving to an integrated approach to capture the interaction between technical systems, organizational structures and human performance within increasingly complex operating environments. This study examines contributions published between 2017 and 2025, focusing on frameworks, assessment methods and operational tools developed to strengthen safety across different plant contexts. To organize the evidence, the analysis applied the CIMO structure, which makes it possible to link the operational setting, the nature of the interventions, the underlying mechanisms and their observable effects on safety performance.

Across the analysed literature, several critical issues emerge. Traditional deterministic approaches remain essential even if limitations in interdependencies between defense levels, ageing infrastructure and variable operating conditions are present. Organizational and human factors continue to play a decisive role, particularly regarding communication, coordination and the ability to maintain consistent practices over time. Studies addressing the representation of safety functions highlight the need for clearer models capable of depicting how systems interact across plant states and defense layers. At the same time, the growing use of immersive training environments- although not yet consolidated- suggest potential improvements in operator preparedness and collaborative tasks.

The review highlights a general shift toward integrating technical, organizational and training-related measures within a more coherent and transparent framework. By the findings of the CIMO model, the study outlines how different approaches contribute to reducing operational risk and improving the reliability of safety-related decisions. The review ultimately provides an integrated perspective that can support the development of adaptable and methodologically consistent safety management practices for current and future nuclear installations.

Keywords: Nuclear plants; Safety Management; Fire safety; Human Organisation Factor; VR simulations; CIMO model.

1. Introduction

In this study Safety Management in nuclear power plants has been examined in depth through a critical literature review and a framework has been introduced. The topic has long been recognized as a pillar of the nuclear industry, where minor events can have severe and huge consequences. Hence, this sector has developed a highly structured framework of technical, organisational, and regulatory practices to ensure that nuclear facilities operate within stringent safety margins. Over the past decades, research has increasingly focused on integrating human factors, organisational culture, risk-informed decision-making, and advanced technological systems into safety management approaches. Drawing on recent studies, this literature review aims to identify current challenges and best practices, and to outline emerging trends for the future of nuclear safety. The well-known nuclear incidental event (Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011) highlighted the potential risks of nuclear power and, consequently, the importance of rigorous safety standards.

Due to the growing worldwide energy demand, nuclear facilities have the potential to sustain those requests, thus their implementation has become a real solution. The priority must first be safety and security in order to implement nuclear facilities. This study arises from this future scenario, more particularly this review arises from the following research questions: how models and frameworks have been applied in the past years regarding safety in nuclear plants; how Human Organisational Factors impact the safety management in nuclear facilities; how technological innovations are implemented to improve safety conditions in nuclear power plants.

The CIMO model is presented to summarise all practical Safety Management operations in nuclear power plants and demonstrate their results. In the context of this literature review, the CIMO frameworks explain how and why different approaches are adopted for risk management in nuclear safety, operator skills, and the reliability of the plans adopted.

The following sections are organized as follows: In section 2 the methodological approach is presented. In section 3 the Safety Management in Nuclear Plants is analyzed, giving the current situation of procedures and issues, including in the subsections the Human Organisation Factors and the current procedures regarding fire safety in nuclear facilities. Section 4 analyzes a modern approach for operator training through VR simulations.

2. Methodology

This literature review considers the temporal range of publications from 2017 through 2025, deliberately chosen to capture the evolution of Safety practices in the post-Fukushima disaster, while keeping relevance to current optional realities.

An exclusive search through Scopus was conducted, selecting the articles with the aim of selecting combined multiple term sets (Articles related to nuclear facilities and power generation, Safety Management and risk control, Human performance and organizational factors, Emerging technologies. Fire protection engineering in nuclear plants).

From this strategy a total of 176 emerges. Focusing more on Direct address to Safety Management Systems, Risk Frameworks or protective methodologies, on organizational structures and human capabilities influence safety assurance and English language a total of 18 studies remained for detailed analysis, each meticulously analyzed with particular attention to the research design and validation of findings. The query research was based as follows: nuclear plants, safety, management, energy production or energy generation.

The organization of this literature review analysis was made with the CIMO model, in Section 2.1, whose structure proves well-suited to complex sociotechnical systems like nuclear power plants.

2.1 Analytical Framework – The CIMO Model

The CIMO model introduced is characterised by 4 areas:

- Context – Nuclear power plants operate in an extremely complex sociotechnical environment, with complex infrastructure, stringent regulations, intense and harsh public scrutiny and differences in culture and security between countries. All this creates dualism in getting production objectives and technological capabilities.

- Intervention – The interventions adopted to improve the Safety of Nuclear power plants include: Integrated Safety Frameworks (ORSAC, Defence-in-Depth), CRM, Organisational and Human factors (HOF) based programs, Virtual Reality (VR) training and Fire Safety Engineering (FSE).
- Mechanism required for these interventions to be effective include greater transparency in Safety functions, more informed and risk-based definitions, greater organisational learning and safety culture, reduced human error, and more accurate modelling of fire scenarios.
- Outcomes – observed results include a significant reduction in operational risk, an overall improvement in nuclear power plant safety performance, increased operator skills, a lower incidence of serious accidents, and increased trust among regulators and the public.

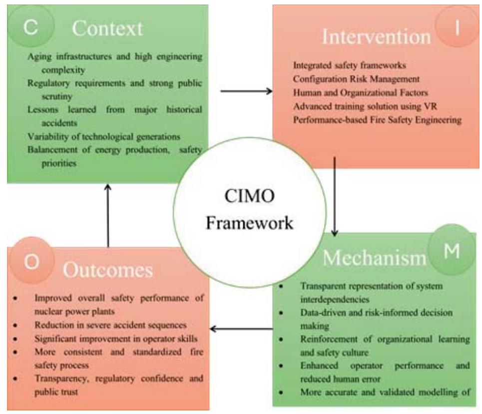

Figure 1 The CIMO model

Table 1 summarises, through the application of CIMO model, key studies in nuclear safety management:

Context	Intervention	Mechanism	Outcome	Source
High system complexity	ORSAC framework	Increased transparency of safety functions	Identification of structural vulnerabilities	Hyvarinen et al. (2022)
Rapid expansion of 2nd-3rd gen reactors	CRM evolution in China	Configuration control; risk-informed operational decisions	Lower CDF; better alignment between maintenance and configuration	Chu et al. (2025)
Post-Fukushima resilience requirements	DEC quantitative method	Reduction of expert-judgement bias; structured scenario filtering	DEC-B reduction; more consistent resilience strategy	Courtin et al. (2024)
Ageing plants; conflicting organisational priorities	Safety culture & management processes	Learning, communication, prioritisation mechanisms	Improved organisational reliability; reduced operational tensions	Kettunen et al. (2007)
Increasing need for realistic operator training	VR-based training systems	Enhanced situational awareness; embodied learning	+9% theoretical and +14% practical performance	Satu et al. (2024)
High-uncertainty fire scenarios	Fire safety engineering + PSA	Realistic modelling; probabilistic risk quantification	Improved fire scenario understanding; better compliance	Dey (2024); Zuo et al. (2012)

Table 1 Application of the CIMO framework to key studies in Nuclear Safety Management

3. Safety Management in Nuclear Plants

In Safety Management for the Nuclear Plants, gaps in existing approaches and proposing frameworks to reinforce current regulatory practices are present. (Hyvärinen et al., 2022) focus on the importance of technical elements—such as physical barriers, protective systems, and Defence-in-Depth (DiD) based on three physical barriers such as the fuel sheath, the reactor system, and the containment structure. Their study introduces the Overall Safety Concept (ORSAC), a framework that transparently represents Safety functions and integrates multiple defensive mechanisms into a single matrix where each barrier operates within specific limits and retains its own safety margins in order to compensate for uncertainties in loads and resistance and must correspond to distinct damage mechanisms.

ORSAC arranges these relationships into a matrix where DiD levels form the columns, and safety functions the rows. This arrangement allows analysts to examine dependencies between systems, compare alternative plant concepts, and identify structural vulnerabilities. The authors demonstrate that, contrary to assumptions within some regulatory frameworks, only two to three DiD levels can be considered genuinely independent. The study limit consists of the absence of cybersecurity integration, despite the potential for cyberattacks to compromise several defence layers simultaneously.

(Ylönen & Björkman, 2023) expands by analyzing the convergence of process safety, physical protection, and cybersecurity. They observe that the traditional approach considers separately Safety and Cybersecurity, preventing consideration of risks that span both domains. Although the International Atomic Energy Agency (IAEA), (Langlois, 2013) integration, Local National approaches vary substantially. The IAEA proposed Integrated Management of Safety and Security (IMSS), aims to be a procedure for both accidental and intentional events, including cyber-induced scenarios.

Further developments appear in the work of Chu et al. (2025), who examine the evolution of Configuration Risk Management (CRM) in China. The rapid expansion of second- and Management Systems, since older units show higher Core Damage Frequency (CDF). has introduced technical guidelines and the deployment of advanced monitoring tools. Despite this, some technical areas remain under refinement although third-generation plants has a lower baseline risk.

(Yang et al., 2019) propose a dynamic risk-based framework for analysing operational tasks in nuclear plants. Their model links human error identification with system configuration management and uses deviations between average risk timelines and point-in-time risk profiles to map human-related vulnerabilities. The framework transforms traditional Probabilistic Safety Assessment into a Living PSA supported by virtual-reality tools. However, it still lacks real-time IoT integration and does not incorporate machine learning to detect emerging risk patterns.

(Courtin et al., 2024) develop a quantitative method for identifying Design Extension Conditions (DEC) and assessing the contribution of post-Fukushima measures, including FLEX strategies, which are the whole of measurements and equipment developed after the Fukushima incident (Xu & Zhang, 2022), and the Seal Depressurization System (SDS). Applying their 11-step method to the SPAR-CSN model, which is the Probabilistic Risk Assessment (PRA), (Park et al., 2024), model standardized by the Nuclear Regulatory Commission (NRC), for Spanish PWRs, the authors reduce 182 DEC-A sequences to 15 and demonstrate a major reduction in reliance on DEC-B measures. Nevertheless, the approach remains bound by its national context and depends heavily on operator actions.

Organisational challenges are highlighted in earlier work by Kettunen et al. (2007), who analyse tensions in European nuclear organisations, including ageing structures, conflicting priorities, and the need to identify safety-critical features amidst commercial pressures. The Tokaimura accident illustrates the consequences of misaligned goals. Effective safety management, they argue, requires clear responsibilities, robust procedures, and a strong safety culture. Finally, Felix Orikpete and Raphael Ejike Ewim (2024) emphasise the foundational role of human factors, noting that cognitive, social, and organisational determinants strongly influence both safety culture and overall organisational performance. However, the study does not address how emerging technologies—such as AI-assisted decision systems—could help mitigate human error in contemporary plants.

3.1. Human Organisation Factors

In (Schöbel et al., 2022), it offers a 50-year review of deep analysis in the European nuclear sector, with an understanding of Human Organisation Factors (HOF). The paper analyzes three principal incidents: the Three Mile Island incident in 1979, Chernobyl in 1986, and Fukushima in 2011. Each incidental event has improved the comprehension of the HOF: in fact, great attention is given to elements such as the importance of control ergonomics, the human-machine interface, the advanced training of the operators, Safety culture, the ambiguity of responsibilities, the procedures qualities and the organisational values.

The authors also discussed the Learn Safe Project implemented to identify the challenge related to nuclear safety, the functional activities that promote safety, and the factors that facilitate or hinder organisational understanding. European managers highlighted eight main challenges, some of which they regard as economic pressures, Human Resource Management, public trust, and safety culture. In 2019, 21 European interviewed managers discussed the aging of the nuclear plants, competitive pressures, and variations in politics and norms. However, the results vary from State to State: in Finland, construction of new plants continues, while in Germany, the introduction of nuclear power has radically altered resources and priorities. Major developments included the formalisation of procedures, the introduction of safety committees, and the implementation of human performance programs.

Despite the progress, many issues remain in HOF management, mostly due to difficulties in correctly interpreting data from self-assessment. The internal and external dynamics of the HOF are still complex and interconnected and the decision-making remains incomplete, and there is a need to improve collaboration between academia and industry. The study, however, is limited to the European context, though there is no other evidence from other Countries. There is no prediction on how HOF will evolve with the integration of Artificial Intelligence, and there is still insufficient treatment of cultural diversity in multinational organisations.

3.2. Fire Safety in Nuclear Plants

Fires are a critical risk factor in nuclear power plants because they can damage critical redundant systems for reactor cooling. Following serious accidents such as the Browns Ferry (1975) accident, increasingly complex regulations have been developed but they are complex to apply, and not always suitable for modern plants. To evaluate the reliability of fire-modelling tools, five countries collaborated in the International Collaborative Fire Modeling Project (ICFMP). The initiative carried out five benchmark studies comparing model predictions with experimental data for switchgear-room fires, large complex structures such as turbine halls, under-ventilated fires, pool fires, and fire spread in cable trays. The simulations showed that most models were able to track the development of the smoke layer with acceptable precision. In contrast, estimating radiative heat and predicting cable failure remained difficult. Estimating the Heat Release Rate (HRR) remains difficult, particularly for cable fires, where ventilation and the thermal properties of surrounding surfaces strongly affect the outcome. Model verification uses both blind tests, which offer greater independence, and open tests, which are easier to conduct. Both have merit, but a common framework is still needed.

Three ISO standards now provide such a structure: ISO 23932-1, (International Organization for Standardization 2018), sets out the basis for performance-based fire engineering; ISO 16730-1, (International Organization for Standardization 2023), explains how calculation methods should be verified and validated; and ISO/IEC TR 17032 (International Organization for Standardization & International Electrotechnical Commission. 2019) outlines the certification of the overall process. Together, they form a consistent system for designing, assessing and certifying fire-safety measures, supporting higher plant safety and improving international alignment. The process has significant management and maintenance costs, in addition to technical difficulties in modelling complex fires, especially under-ventilated fires and cable fires.

The adoption of the ISO standards presented can significantly improve safety and support the growth of nuclear energy as a low-carbon energy source, (Dey, 2024).

These standards require high model reliability, as their effectiveness depends heavily on the data provided. The operating conditions, scenarios, analyst expertise, and input data must be considered with extreme precision and accuracy. However, the procedures must be implemented with the right processes and appropriate models. Moreover, many countries with traditional regulations and inexperienced with FSE may have significant difficulties implementing these standards.

Furthermore, nuclear power plants require an in-depth, context-specific analysis of the fire safety protocols to be adopted, ensuring worker safety from radiation exposure. The Probabilistic Safety Assessment (PSA), (Park et al., 2024), uses probabilistic theories to analyses the potential risks of dangerous events, the likelihood of their occurrence, and to identify the main sources of fire risk. The purpose of the PSA is cited in NUREG/CR-6850 (U.S. Nuclear Regulatory Commission & Electric Power Research Institute. 2005), which currently represents the most comprehensive and advanced assessment for probabilistic fire safety. The probabilistic Fire Safety analysis is based on a design, and the calculations are performed in the Fire Dynamics Simulator (FDS) model, which is designed to optimise the process. The PSA model, however, considers only reasonable, resolvable events that can be treated with a descriptive approach, but does not consider catastrophic, unexpected situations. Clearly, this process requires experts and engineers with the necessary skills and capabilities, and therefore requires the resources to apply this model, which are not always available. (Zuo et al., 2012)

Many modelling errors depend more on the modeler's expertise than on the application software. The human factor, previously overlooked, must be given due weight. (Wen, 2024)

4. Modern solutions: VR approach

The current literature on Safety Management in nuclear power plants has shown significant interest in modern technologies, offering ideas and frameworks for their application in this context. In (Satu et al., 2024), the importance of the role of Field Operators (FOP) in nuclear power plants, which have the critical responsibilities of monitoring the processes on the field, verifying the sensor's state, and the validation of their results, equipment operations, preventive maintenance activities, and diagnostic actions in emergencies.

In the study, a simulator is integrated to recreate a fixed Main Control Room (MCR) and the Virtual Reality (VR) ambient for FOP and many simulations were conducted. Furthermore, a 3D projection system for preventing liquid butane leaks and fire scenarios in the oil and gas industry was implemented. These simulations helped to establish guidelines for the mutual understanding of activities between operators

The training was meant for complex and rare procedures, such as planning work to minimise the radiation exposure, diffusion and concentration of radiation. Multiple specific exams were considered, focusing on the VR context. Many training courses on high-voltage scenarios were taken by simulating circuits and their behaviour under stress conditions. The simulated VR environment provides an online system with real-time tracking and optic and auditory feedback to increase operators' awareness and minimise radiation exposure risk, reduce the operator's workload, thus improving health management, and reduce costs.

Many other simulations were conducted to compare traditional teaching methods with VR preparation, and in most of them, all VR-prepared users outperformed the traditional methods. Several VR-based training studies reports mixed but generally positive outcomes. In confined-space inspections, VR-trained operators achieved higher exam performance due to prior familiarization with the environment. In tank-suspension preparation, results were comparable between VR and traditional instruction. Conversely, in electrical line maintenance, VR training not only yielded superior operator performance but also reduced company training costs by approximately 33%.

The VR approach proved more effective than most current teaching methods, largely thanks to the great computational power and the precision with which actions' effects and consequences are modelled. One of which concerns radiation visualisation, where users were provided with a 3D map, significantly increasing their performance. Key factors influencing the effectiveness of VR-based training include the alignment with learning objectives, the design of scenarios focused on specific skills. Effective programmes also require high-level guidance, adaptation to the learner's experience, especially for unfamiliar tasks—and opportunities for active engagement, which consistently enhance learning outcomes.

Several challenges such as technical constraints, few validated scenarios, regulatory barriers, and substantial implementation costs still limit a widespread adoption.

5. Discussion

The aforementioned studies show how Nuclear Safety Management has progressively developed and improved. In fact, the importance of Human Factor and the use of new technologies are crucial. However, from literature it arises the limitations of traditional assumptions regarding the independence of defence layers and underline the need for frameworks capable of capturing interdependence within complex plant architectures. These findings reinforce the idea that the performance of engineered systems ultimately depends on the quality of communication, leadership, and decision-making within the operating organisations. Technological developments, particularly Virtual Reality, offer promising support for strengthening operator readiness. VR enhances situational awareness, improves collaboration between field operators and control room staff, and enables realistic rehearsal of scenarios that are difficult to train through conventional means. Yet its widespread adoption depends on scenario fidelity, data quality, and clear pedagogical structures, alongside regulatory updates that can accommodate digital training environments and associate cyber considerations. The examined studies portray a safety landscape that is becoming more methodologically sophisticated and complex. Advancing nuclear safety will require stronger integration of risk-informed methods, mature organisational practices, and carefully validated technological innovations that support reliable, transparent, and resilient plant operations.

Hence, a conclusive framework is proposed to illustrate how technical measures, organisational processes, human performance, and contextual factors converge to shape overall safety outcomes. This integrative view highlights the mechanisms through which interventions operate and clarifies their contributions to reliable nuclear plant operation.

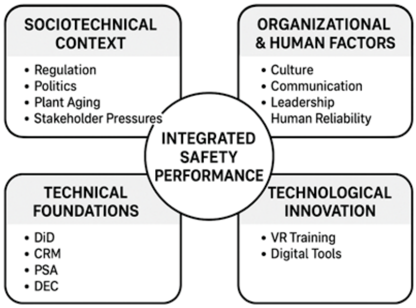

Figure 2: Integrated safety performance

- Technical Foundations

Defence-in-Depth, CRM, PSA, DEC quantification, and fire-protection engineering provide the structured basis for preventing, controlling, and mitigating abnormal conditions.

- Organisational & Human Factors

Leadership, safety culture, communication quality, human reliability, and the ability to learn from past events determine how effectively technical systems perform in real operating environments.

- Sociotechnical Environment

Regulatory expectations, political pressures, plant ageing, economic constraints, and stakeholder dynamics shape long-term strategic and operational safety decisions.

- Technological Innovation

VR-based simulation enhances operator readiness, improves team coordination, and offers realistic and adaptive training pathways, though its full adoption remains dependent on data availability and regulatory acceptance.

6. Conclusion

The studies examined illustrate that deterministic approaches remain essential, but they are no longer sufficient when considered in isolation. Modern plants operate amid increasing variability, aging infrastructure, and evolving regulatory expectations; as a result, safety depends on integrated, transparent, and risk-informed methods. Research on organisational and human factors reinforces this direction: persistent tensions linked to communication, leadership, and long-term learning continue to influence the practical performance of technical systems. Likewise, recent work on Virtual Reality training suggests that targeted technological interventions can strengthen operator readiness and situational awareness, though the extent to which these tools can be adopted remains constrained by regulatory and practical constraints. Seen through the lens of the CIMO model, the reviewed contributions point to a familiar pattern: the context of nuclear operations is complex and dynamic; interventions range from analytical frameworks to training technologies; their mechanisms work only when supported by sound organisational processes and well-designed human–technology interactions. Taken together, the evidence indicates that nuclear safety emerges from the coordinated functioning of multiple domains, not from any single component acting alone. Strengthening safety in the coming years will require refining analytical tools, sustaining investment in human and organisational factors, and carefully integrating new technologies to support safe and resilient nuclear operations.

Given the growing global demand for electricity, the deployment of nuclear power plants, used as energy sources, is certainly a major development in the energy sector. The key to the deployment of nuclear power plants is to ensure they meet all safety requirements. Given the current situation, despite the shortcomings highlighted and identified in the study and analysis conducted in this literature review, updates regarding safety are expected, aimed at supporting the installation of future nuclear power plants.

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