International Regulatory Frameworks for AI in Nuclear Power Plants and Implications for Domestic Policy Development

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Keywords : International regulatory framework, AI, Nuclear power plant, Domestic Policy, Policy implications

1. Introduction

Artificial Intelligence (AI) is a collective term for computer algorithms that mimic biological mental processes or activities, such as learning, reasoning, and decision-making [1].

In the nuclear sector, AI and machine learning (ML) are being integrated into diverse domains, including thermal-hydraulics simulation, in-core fuel management, and reactor core design. Recent studies have demonstrated that AI-driven models can achieve significant computational acceleration—up to 100,000 times faster than original simulation tools—while maintaining satisfying accuracy. However, the non-deterministic "black-box" nature of these models conflicts with existing deterministic regulatory frameworks optimized for static software [2].

In response, South Korea enacted the "Basic Act on the Development of Artificial Intelligence and the Establishment of Foundation for Trustworthiness" (AI Basic Act) to foster innovation and ensure a trustworthy AI infrastructure [3].

As AI systems evolve toward higher autonomy, a more granular regulatory approach is required to bridge the gap between AI legislation and the unique safety requirements of nuclear power plants (NPPs).Therefore, it is imperative to establish regulatory frameworks specifically tailored for the utilization of AI in the nuclear sector.

To that end, this study analyzes the regulatory trends of international agencies and conducts a comparative analysis with the existing AI Basic Act to identify necessary improvements for the domestic framework. Furthermore, this research proposes the Risk-Informed, Performance-Based (RIPB) methodology as a key solution to supplement and refine the AI Basic Act, ensuring both technological innovation and nuclear safety.

2. Challenges in the Domestic AI Basic Act: The Rigidity of High-Risk AI Definition

A critical feature of the domestic AI Basic Act is the explicit definition of "High-Risk AI." Under the current framework, AI applications are categorized as high-risk based primarily on the domain of application, without sufficient consideration for the specific level of autonomy or the actual impact of the AI's function on safety. In the nuclear industry, where nearly all systems are safety-critical, even simple AI applications intended for auxiliary monitoring or secondary tasks could be classified as "High-Risk AI."

This binary and rigid classification poses a significant challenge, as it may subject operators to redundant and overlapping regulations from both general AI laws and nuclear-specific safety acts. Such regulatory friction inevitably discourages the adoption of AI technologies, highlighting an urgent need for a more differentiated and risk-graded regulatory approach.

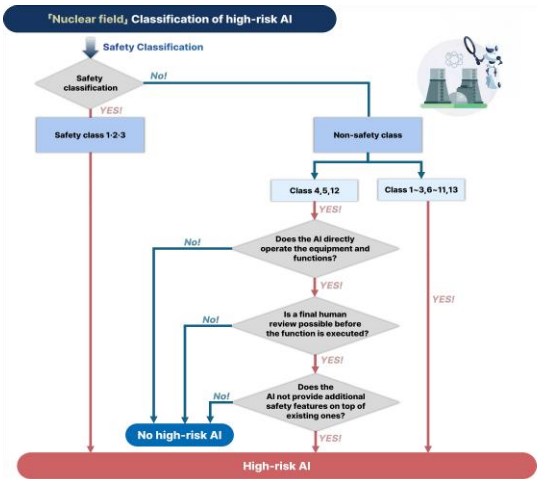

Figure 1. High-risk ai classification in ai basic act

3. International Regulatory Strategies: Tiered Risk and Autonomy

To overcome the limitations of monolithic risk definitions, major international nuclear regulators have adopted strategies that emphasize tiered risk classification and flexibility.

3.1 *US NRC: Strategic Readiness and Graded Oversight*

The U.S. Nuclear Regulatory Commission (NRC) has established a proactive regulatory posture through its "Artificial Intelligence Strategic Plan: Fiscal Years 2023–2027" (NUREG-2261) [4].

This plan is built upon five foundational pillars designed to ensure that the agency remains ready to evaluate AI-based license applications effectively and efficiently. These goals include ensuring regulatory readiness for decision-making, establishing a robust organizational framework for reviews, and strengthening AI partnerships at both national and international levels.

Furthermore, the NRC focuses on cultivating an AI-proficient workforce and pursuing specific use cases to build a foundational AI infrastructure within the agency. By anticipating the broad spectrum of AI sub-specialties—such as natural language processing and deep learning, the NRC seeks to maintain its high standards of safety and security in an increasingly digitized environment.

Figure 2. NRC's artificial intelligence strategic plan

A central element of the NRC's strategy is the conceptual distinction between "automation" and "autonomy."

While automation refers to systems that follow predefined, rule-based logic to perform tasks without external intervention, autonomy involves adaptive systems that can adjust their behavior in response to changing conditions.

The NRC recognizes that as AI systems move toward higher levels of autonomy, the degree of direct human intervention naturally decreases. This shift necessitates more stringent and adaptive regulatory scrutiny to uphold the "Defense-in-Depth" philosophy, ensuring that the reduction in human oversight is compensated by increased system reliability and robust regulatory oversight.

Beyond strategic planning, the NRC has conducted a comprehensive AI Regulatory Gap Analysis (AIRGA) to assess the readiness of the current regulatory framework. As documented in the "Regulatory Framework Gap Assessment for the Use of Artificial Intelligence in Nuclear Applications" (October 2024), the agency evaluated 517 Regulatory Guides (RGs) across ten broad divisions to identify potential barriers to AI adoption. The assessment found that the existing framework is largely capable of accommodating AI technologies, with potential gaps identified in fewer than 100 RGs [5].
These identified gaps were categorized into specific types, such as "implied manual actions" that might conflict with autonomous operations or "special computations" that do not currently account for AI-driven methodologies. This systematic gap assessment provides a critical roadmap for updating regulatory guidance, ensuring that the NRC's oversight remains technically sound as AI transitions from a supporting role to more integrated safety applications.

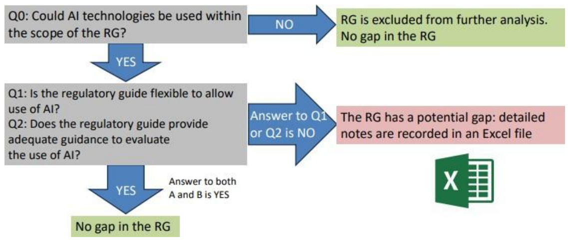

Figure 3. Flow diagram of the screening process for regulatory guides [5]

3.2 *UK ONR: Goal-Oriented Regulation and SAPs*

The UK Office for Nuclear Regulation (ONR) has established a "pro-innovation" regulatory posture that is fundamentally guided by five core value-based principles aligned with the UK government's broader AI strategy [6].

These principles comprising safety, security, and robustness; appropriate transparency and explainability; fairness; accountability and governance; and contestability and redress ensure a consistent and ethical approach to AI deployment across all regulatory functions, including nuclear safety, security, and safeguards.

Figure 4. ONR's regulation principles for ai regulation

Rather than imposing an entirely new set of prescriptive regulations, the ONR utilizes its existing Safety Assessment Principles (SAPs) as a flexible and comprehensive framework to evaluate the safety of AI-based applications. This reliance on SAPs allows the regulator to maintain technological neutrality, focusing on the safe outcomes and behavioral properties of a system rather than the specific underlying technology or coding standards.

However, technical research commissioned by the ONR suggests that while the SAPs are structurally robust, they require specialized interpretation and additional guidance to address the "black box" nature and inherent opacity of machine learning algorithms [7].

For instance, a systematic safety assessment for AI must account for its complexity and lack of predictability, often requiring a "Human-in-the-loop" approach to manage residual uncertainties in high-safety-significance tasks.

To bridge the gap between research and commercial use, the ONR's Innovation Hub plays a pivotal role in minimizing regulatory uncertainty through frequent engagement with duty-holders.

By supporting the use of "Regulatory Sandboxes," the ONR provides a controlled environment where innovative AI solutions can be tested and validated against real-world conditions [8]. This facilitates a smoother transition for disruptive technologies from the R&D stage to full operational deployment while ensuring that the "Defense-in-Depth" principle is never compromised.

This proportionate and outcome-oriented strategy ensures that AI integrated into nuclear licensed sites enhances operational safety and efficiency without creating unnecessary administrative barriers.

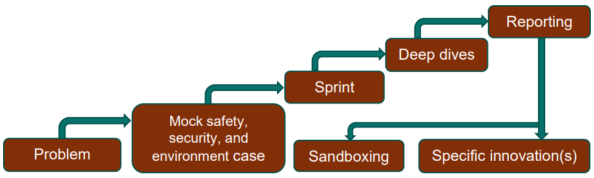

Figure 5. Overview of the sandboxing process [8]

3.3 *Classification based on AI Risk Grading*

A common trend in international regulation is the shift toward grading AI risk based on two primary dimensions: the Level of Autonomy and the Impact on Safety Functions [9].

Instead of a binary "high-risk" label, these frameworks assess how much an AI system influences the reactor's safety margin and the degree of human oversight. This tiered approach prevents redundant regulation and allows operators to utilize AI for a wider range of tasks by applying differentiated requirements.

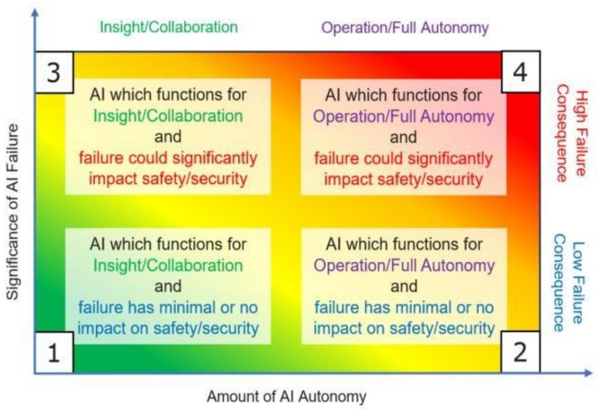

Figure 6. Categorizing ai failure significance and ai autonomy [9]

4. Identification of Improvements for the Domestic AI Framework

In light of evolving international regulatory strategies, it is suggested that the current domestic AI Basic Act undergo careful refinement to better accommodate the specialized safety profiles inherent to the nuclear industry. Rather than maintaining a uniform regulatory approach, it may be prudent to consider a transition toward a risk-informed, tiered system tailored to the specific safety cases of nuclear fields.

Specifically, this study proposes that further deliberation is warranted to determine whether the domestic framework can effectively integrate two pivotal dimensions: the degree of operational autonomy and the functional safety significance of the AI system. It is suggested that an integrated evaluation of these factors could provide a more nuanced basis for calibrating regulatory stringency. Such an approach would aim to foster technological innovation while ensuring that oversight remains proportional to the actual risk posed to reactor safety. Refining these definitions and examining their legal feasibility appears to be a constructive step toward allowing operators to leverage AI technologies more broadly without encountering disproportionate administrative barriers.

5. Conclusions

The successful integration of AI into NPPs depends on a regulatory environment that balances innovation with public safety. The analysis of the US NRC and UK ONR frameworks demonstrates that specialized, risk-aware oversight is superior to monolithic definitions for the nuclear sector.

To maintain global competitiveness and ensure safety, the domestic AI Basic Act should be supplemented with a graded risk classification system that considers the unique autonomy and safety profiles of nuclear AI applications.

This research provides a foundational roadmap for harmonizing domestic policy with international best practices to support the era of digital nuclear energy.

ACKNOWLEDGEMENT

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy of Korea (No. RS-2023-00244330).

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs(RMAS)and the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea.(No. RS-2025-02310358)

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