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Utilization of Artificial Intelligence Technologies for Innovative SMR

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1. Introduction

Innovative Small Modular Reactor (i-SMR) introduce fundamentally different design characteristics compared to conventional large light water reactors, including an integrated reactor vessel, compact steel containment, multi-module deployment, and extended operating cycles.While these features enhance inherent safety and economic flexibility, they also introduce new technical challenges such as limited instrumentation accessibility, increased complexity of operational monitoring, and changes in maintenance strategies. In particular, restricted direct measurement, an expanded operational state space, and reduced on-site staffing significantly increase the need for advanced technologies capable of supporting continuous safety awareness and reliability management. Against this background, artificial intelligence (AI), meta-modelling, and advanced simulation technologies are emerging not as optional enhancements, but as essential enabling technologies for ensuring the safe and reliable operation of i-SMR.

This study presents a conceptual framework that integrates AI-based predictive diagnostics, preventive maintenance, and operator automation in alignment with the safety and reliability objectives of i-SMR. In addition, human factors considerations and regulatory concerns associated with the application of such advanced technologies are discussed, together with corresponding mitigation strategies.

2. Need for AI technology

AI and advanced simulation technologies can be systematically applied across several key domains. AI-based predictive diagnostics and preventive maintenance enable the estimation of degradation trends and remaining useful life of critical components, thereby preventing unanticipated failures and supporting risk-informed maintenance strategies. For safety-aware operational monitoring, a meta-model based digital twin integrates operational data with validated safety analysis results, providing a means to continuously compare and assess actual plant conditions against expected system behavior. Furthermore, AI-driven insights derived from long-term operational data can be fed back into design validation and future SMR design improvements, supporting reliability-centered design decision-making. The scope of applicable AI technologies encompasses machine learning-based anomaly detection, physics-informed neural networks for state estimation under limited sensor coverage, natural language processing for procedure management and alarm rationalization, and reinforcement learning for adaptive control room interface optimization. These technologies are particularly well-suited to address the instrumentation constraints inherent to the integrated reactor vessel design of i-SMR, where traditional direct-measurement approaches are physically limited. By combining real-time plant data with high-fidelity simulation results, AI-enabled systems can construct a continuously updated probabilistic picture of plant health, providing operators with actionable information that goes beyond conventional alarm-based interfaces. This shift from reactive alarm response to proactive condition awareness represents a fundamental improvement in the safety culture and operational discipline achievable within a reduced-staffing, multi-module environment.

Importantly, these functions are defined as predictive and advisory capabilities that support safety, rather than replacing deterministic safety systems or reactor protection functions. i-SMR are expected to be operated by a limited number of operators supervising multiple modules, making increased cognitive workload and the potential for human error key considerations. The challenge is compounded by the extended operating cycles and passive safety systems characteristic of i-SMR, which alter the nature of transient response and shift operator responsibilities away from active intervention toward continuous monitoring and early diagnosis. In this environment, the risk of mode confusion, attention tunneling, and decision fatigue is significantly elevated relative to conventional single-unit operations. AI-based support tools must therefore be designed not only to present information efficiently, but to actively manage the operator's cognitive state—flagging when attention is required, suppressing irrelevant data during off-normal events, and providing clearly ranked recommendations that reduce the time pressure associated with multi-module abnormal condition management.

AI-assisted operator automation can support operators by enhancing situation awareness, prioritizing information, and providing early warnings of emerging abnormal conditions.

From a human factors perspective, such technologies should satisfy the following principles:

- Reduce cognitive workload without inducing excessive reliance on automation
- Ensure transparency and explainability of AI-generated outputs
- Maintain final decision-making authority with human operators

3. Function and Concept of AI operation support systems for i-SMR

A critical enabler for realizing these benefits is the multi-module integrated control room concept inherent to the i-SMR design. Operating multiple reactor modules simultaneously from a single control room significantly reduces staffing requirements but substantially increases the complexity of each operator's cognitive responsibilities. To make such an operational configuration both feasible and safe, advanced operator support systems and AI technologies are not merely beneficial—they are prerequisites. The i-SMR design achieves an approximately 1,000-fold improvement in Core Damage Frequency (CDF) compared to large conventional nuclear power plants; however, this enhanced safety margin must be actively preserved during plant operation. Operator support systems must therefore be capable of proactively detecting any reduction in safety margin before it progresses to a safety-significant condition, enabling timely corrective action within the operational decision cycle. In this context, AI technologies play a dual role: on one hand, they serve to reduce human error by augmenting operator situation awareness, filtering spurious alarms, and providing context-sensitive procedural guidance across multiple simultaneously monitored modules. On the other hand, it is essential that AI systems do not directly intervene in safety functions. The boundary between advisory support and autonomous safety actuation must remain clearly defined and rigorously enforced, consistent with the deterministic safety philosophy governing nuclear operations. AI must remain a decision-support layer rather than a decision-making actor within the safety function hierarchy. Ultimately, the overarching objective of integrating AI and advanced operator support technologies into the i-SMR operational concept is to enhance the overall reliability of plant operation—not only by reducing the frequency of human error, but by ensuring that the operational state remains within well-characterized safety boundaries at all times, that anomalies are detected with sufficient lead time for human response, and that the cognitive burden on operators is managed to a level consistent with sustained high-performance decision-making across extended multi-module supervisory duties.

By positioning AI not as a direct safety function but as a human-centered, safety-supporting technology, i-SMR can effectively leverage advanced digital capabilities while preserving deterministic safety philosophy and a human-in-the-loop operational concept. The functional architecture of an AI-based operator support system for i-SMR can be conceptually organized into three integrated layers. The first is a real-time data fusion and state estimation layer, which aggregates signals from distributed sensors across multiple modules, applies physics-informed models to infer unmeasured parameters, and maintains a continuously updated representation of plant state. The second is a diagnostic and prognostic reasoning layer, which applies trained models to detect deviations from normal operating envelopes, classify emerging fault signatures, and project the likely evolution of plant conditions over relevant time horizons. The third is an operator interface and advisory layer, which translates the outputs of the lower layers into operator-actionable information—presenting situation summaries, prioritized alert sequences, and procedure recommendations in a format optimized for the cognitive demands of multi-module supervision. Across all three layers, the system must be designed to maintain full auditability and explainability. Operators must be able to interrogate the basis for any AI-generated recommendation, and the system must degrade gracefully under sensor failures or out-of-distribution plant conditions, flagging its own uncertainty rather than producing overconfident outputs. These requirements align closely with the principles of trustworthy AI increasingly articulated in emerging nuclear regulatory guidance, and they represent a necessary foundation for gaining regulatory acceptance of AI-assisted operations in safety-critical nuclear environments.

4. Conclusions

This study has examined the role of artificial intelligence and advanced simulation technologies as essential enabling capabilities for the safe and reliable operation of i-SMR. The unique design characteristics of i-SMR—including multi-module deployment, integrated reactor vessel configuration, passive safety systems, and reduced on-site staffing—collectively create an operational environment that cannot be adequately supported by conventional instrumentation and control approaches alone. AI-based predictive diagnostics, digital twin-enabled safety monitoring, and intelligent operator support systems represent a coherent and necessary response to these challenges, provided they are implemented within a framework that respects the primacy of deterministic safety functions and preserves human decision-making authority.

The analyses presented in this study lead to several key findings. First, the multi-module integrated control room concept central to i-SMR operation cannot be safely or sustainably realized without advanced AI-based operator support. The approximately 1,000-fold improvement in Core Damage Frequency that i-SMR design achieves over large conventional plants represents a safety margin that must be actively preserved during operation; AI-enabled systems that proactively detect reductions in safety margin before they become safety-significant are therefore not optional enhancements but operational necessities. Second, while AI technologies offer substantial potential for reducing human error through enhanced situation awareness, alarm rationalization, and context-sensitive procedural guidance, the boundary between advisory support and direct intervention in safety functions must remain inviolable. AI must function as a decision-support layer, not a decision-making actor, and the deterministic safety philosophy governing nuclear operations must be fully preserved. Third, the three-layer functional architecture proposed in this study—comprising real-time data fusion and state estimation, diagnostic and prognostic reasoning, and operator interface and advisory functions—provides a coherent framework for deploying AI capabilities in a manner that is both operationally effective and regulatorily defensible. Transparency, explainability, and graceful degradation under uncertainty are non-negotiable design requirements for each layer. Fourth, realizing these capabilities requires sustained investment in high-fidelity simulation environments, operator-in-the-loop testing, and the accumulation of operational data that can progressively validate and refine AI model performance over the plant lifecycle.

Looking toward a practical roadmap for AI deployment in i-SMR, a phased approach is recommended. In the near term, priority should be given to AI applications in condition monitoring and predictive maintenance, where the consequences of imperfect predictions are bounded and the regulatory pathway is relatively well established. In the medium term, digital twin-based safety margin monitoring and AI-assisted alarm management can be introduced as operator advisory tools, supported by extensive simulator validation and human factors testing. In the longer term, as operational data accumulates and regulatory confidence grows, more sophisticated AI-driven operator support functions—including multi-module abnormal condition management assistance—can be deployed with appropriate oversight mechanisms in place. Throughout this roadmap, international cooperation on AI standards for nuclear applications, including engagement with the IAEA, NRC, and other national regulators, will be essential to ensure that the i-SMR program benefits from and contributes to the global knowledge base on trustworthy AI in nuclear safety-critical systems.

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