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Conceptual Framework, Implementation Elements, and Regulatory Considerations of Digital Twin Technologies in Nuclear Applications

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1. Introduction

As nuclear power plants (NPPs) face increasingly complex operational challenges—such as extending the lifespan of aging infrastructure, complying with tightened international safety regulations, and preserving operational expertise in a rapidly retiring workforce—the integration of digital twin (DT) technologies has emerged as a transformative approach. DTs combine data-driven and physics-based modeling to create a dynamic, virtual representation of physical assets and systems, enabling real-time mirroring of plant behavior. In the nuclear domain, this capability offers the potential for predictive maintenance, enhanced decision-making, optimized operational efficiency, and improved safety margins. While DTs have been successfully deployed in industries such as aerospace, advanced manufacturing, and process engineering, their implementation in the nuclear sector presents unique challenges due to stringent regulatory oversight, high safety and reliability requirements, and legacy system constraints.

2. Methods

This study synthesizes and critically analyzes six technical reports published by the U.S. Nuclear Regulatory Commission (NRC), including Technical Letter Report TLR-RES/DE/REB-2021-01 and related R&D documentation, to assess the current state-of-the-art in DT technologies for nuclear applications. The review addresses:

(1) NRC definitions, classification criteria, and distinguishing attributes of DTs in nuclear contexts;
(2) Technical implementation elements, including advanced sensor networks, AI/ML-based analytics, high-fidelity physics simulation, and cyber-physical integration frameworks
(3) Global R&D trends, readiness level assessments, and cross-industry lessons learned.

Special emphasis is placed on regulatory considerations, such as model validation and verification (V&V) methodologies, data quality management, cybersecurity measures, and the integration of DT systems into nuclear safety licensing frameworks.

3. Results

The analysis identifies a five-component functional architecture—data acquisition, communication, analytics, integration, and control—as the backbone for DT deployment in nuclear facilities. Each component is mapped to enabling technologies and operational functions, from sensor calibration and IoT-based data transmission to hybrid physics–AI modeling and closed-loop control systems. Case studies include applications in small modular reactors (SMRs) for operational optimization, as well as pilot projects in aging NPPs aimed at extending component life and improving condition-based maintenance. These examples illustrate that DT-enabled predictive analytics can significantly reduce unplanned outages, support risk-informed decision-making, and enhance lifecycle asset management. However, persistent gaps exist in the trustworthiness of DT models, the standardization of digital frameworks, and the validation of cyber-physical interfaces under NRC safety requirements. The review also identifies seven major technical challenges, including sensor network modernization, data fusion under heterogeneous system constraints, uncertainty quantification in coupled models, and cybersecurity resilience.

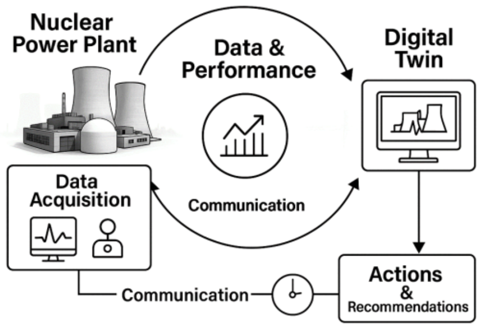

Figure 1. Schematic representation of the five functional elements (Information Acquisition, Communication, Analytics, Integration, and Control) for Digital Twin implementation.

3. Conclusions

Digital twins have the potential to fundamentally enhance the safety, efficiency, and sustainability of nuclear power operations, particularly in addressing the needs of aging plants and emerging SMR designs. Realizing this potential will require coordinated advancements in technology, regulatory adaptation, and workforce capability development. In the short term, phased implementation roadmaps—starting with partial DT prototypes focused on critical systems—can serve as testbeds for V&V methodologies and regulatory acceptance. In the longer term, an ecosystem-level integration of DT technologies across plant design, operation, and decommissioning stages could enable a fully digitalized nuclear lifecycle. This study provides a consolidated framework for DT adoption, offering policy recommendations, R&D priorities, and international collaboration strategies to accelerate DT integration in Korea and beyond.

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