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Failure Mode Analysis and Configuration Management for Digital Instrumentation and Control Upgrades in Ageing Nuclear Power Plants

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Abstract
The modernization of ageing nuclear power plants requires careful reconciliation of technological advancement with established safety obligations. This review examines how failure mode analysis and configuration management can support reliable digital instrumentation and control upgrades while addressing equipment deterioration, obsolescence, software vulnerabilities, and integration risks. A structured narrative review and thematic synthesis of nuclear engineering literature, regulatory guidance, and related reliability studies published through 2025 were undertaken. The analysis considered system architecture, hardware and software failure mechanisms, probabilistic safety assessment, configuration control, verification, cybersecurity, and emerging diagnostic technologies. The findings indicate that digital upgrades can improve monitoring, fault identification, and maintenance planning, but also introduce systematic software defects, common-cause failures, shared communication dependencies, and potentially consequential cyber threats. Ageing analogue interfaces and incomplete engineering records further complicate replacement decisions. Failure mode and effects analysis, fault-tree modelling, and probabilistic safety assessment provide complementary frameworks for identifying vulnerabilities and evaluating their significance, although uncertainty and limited failure data constrain quantitative conclusions. Configuration baselines, requirements traceability, authorized changes, and independent verification emerge as essential safeguards for preserving alignment between installed equipment and the approved design basis. Predictive diagnostics and digital twins offer additional opportunities, provided their performance is validated for intended applications. The review concludes that successful modernization depends on integrated technical and organizational assurance rather than equipment substitution alone. It recommends phased, risk-informed upgrades; rigorous common-cause and cybersecurity assessments; qualified interface testing; auditable configuration records; and sustained regulatory engagement. Further research should strengthen software reliability evidence and validation methods for emerging diagnostic tools in safety-related environments across successive phases of extended operation.

Keywords: *Digital Instrumentation and Control; Nuclear Power Plant Ageing; Failure Mode Analysis; Configuration Management; Probabilistic Safety Assessment; Digital Modernization.*

1. Introduction

1.1. Background to Nuclear Plant Digital Modernization

Digital modernization has become an important component of sustaining the operational safety, reliability and economic viability of ageing nuclear power plants. Many facilities were commissioned with analogue instrumentation and control (I&C) architectures comprising hardwired logic, electromechanical relays, discrete indicators and specialized monitoring equipment. Although these systems have established operating histories, prolonged service introduces component degradation, diminishing spare-parts availability and increasing difficulties in retaining manufacturer support. The International Atomic Energy Agency identifies physical ageing and technological obsolescence as distinct but interacting pressures that necessitate planned modernization rather than indiscriminate equipment replacement (IAEA, 2022).

Digital I&C technologies offer programmable control, improved diagnostic resolution, more flexible information presentation and coordinated processing of plant measurements. Their deployment, however, changes the character of system dependencies: functions once implemented through separate hardware may become concentrated in shared processors, networks or software platforms. Architectural comparisons by Ibrahim and Sallam (2014) demonstrate why diversity, functional separation and system-level reliability are central to evaluating nuclear control designs. Consequently, modernization must preserve the independence and performance of safety functions while accounting for interactions between new digital equipment and retained analogue subsystems. Experiences from industrial automation provide a complementary perspective on engineering integration. In a Nigerian study, Sunday and Omoegun (2022) examined Siemens Totally Integrated Automation Portal as a framework for coordinating programmable controllers, human–machine interfaces and engineering information. Such integration illustrates the practical value of standardized development environments, but application to nuclear facilities requires additional qualification, lifecycle documentation and regulatory scrutiny. The distinction is fundamental because operational convenience cannot substitute for demonstrable safety performance in reactor protection and engineered safety-feature actuation systems.

Evidence from Egyptian researchers further emphasizes the importance of dependability in digital reactor protection. Torkey et al. (2020) developed a Bayesian belief-based approach for examining reliability improvement, illustrating how structured probabilistic reasoning can expose relationships among components and potential failures. Digitalization therefore creates opportunities for more systematic reliability evaluation while simultaneously requiring explicit consideration of software behavior, signal processing and dependency structures that are less visible in conventional equipment.

Actual implementation experience reinforces the need for disciplined modernization planning. Hunton et al. (2023) described the initial scoping of a safety-related digital I&C pilot upgrade in the United States, highlighting the importance of coordinating technical design with licensing and implementation expectations. Before installation, operators must establish functional requirements, assess interfaces, confirm operating constraints and document how upgraded configurations will satisfy the approved safety basis. Configuration management accordingly becomes a continuing engineering responsibility, extending across design revisions, testing, maintenance and subsequent software modifications.

Failure analysis is especially consequential because digital platforms may introduce shared vulnerabilities across nominally redundant channels. Bao et al. (2023) examined common-cause failures in safety-related digital I&C systems, showing the relevance of evaluating both hardware and software contributions to overall plant risk. An apparently localized design defect can have

broader implications when identical logic, equipment or dependencies are replicated throughout a protective architecture.

Risk assessment must therefore accompany modernization from initial concept through commissioning and operation. Zhang et al. (2023) developed an integrated assessment approach for safety-related digital I&C, supporting evaluation of failure scenarios alongside their potential consequences. Cybersecurity adds another dimension: connectivity, maintenance interfaces and digital communications create pathways requiring systematic threat assessment, access restrictions and defensible security boundaries (Zhang & Kelly, 2023). For ageing nuclear plants, effective digital modernization is thus a controlled transformation of safety-critical assets in which reliability evidence, traceable configurations and operational continuity are as important as technological capability over extended lifetimes.

1.2. Ageing Infrastructure and Instrumentation Reliability Challenges

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Ageing nuclear infrastructure presents significant reliability challenges as instrumentation and control (I&C) components experience prolonged exposure to radiation, elevated temperatures, humidity, electrical stress, and mechanical vibration. These conditions accelerate deterioration in sensors, electronic circuits, cable insulation, and signal transmission systems, potentially compromising reactor monitoring and safety functions. Online monitoring techniques provide opportunities for identifying sensor degradation and measurement inaccuracies before functional failure occurs, provided diagnostic procedures are appropriately validated (Hashemian, 2010).

Technological obsolescence further complicates infrastructure reliability, particularly when manufacturers discontinue essential processors, circuit boards, and calibration equipment. Consequently, maintenance strategies must balance equipment replacement, component availability, qualification requirements, and operational continuity. Integrated ageing assessments incorporating remaining service life, failure probability, and economic considerations can support informed modernisation decisions (Chen et al., 2025). Similarly, ageing management practices at South Africa's Koeberg Nuclear Power Station emphasise systematic condition assessment, configuration control, and regulatory compliance throughout extended plant operations (Eskom Holdings SOC Ltd, 2022). Condition-based maintenance offers an alternative to predominantly corrective interventions by integrating equipment monitoring, failure analysis, and preventive planning. Predictive maintenance approaches demonstrate how systematic operational data assessment can support earlier fault identification and maintenance scheduling (Sunday et al., 2020). However, nuclear applications require qualified instrumentation, conservative acceptance thresholds, and documented safety evaluations.

Machine-learning techniques offer additional possibilities for anomaly detection, fault classification, and remaining-useful-life prediction, although limited failure datasets, operational variability, and interpretability concerns constrain their practical reliability (Xu et al., 2023). Accordingly, effective ageing management requires integrating validated diagnostics, periodic calibration, independent safety verification, and comprehensive maintenance documentation. Modernisation initiatives must preserve system compatibility, functional independence, and configuration integrity while distinguishing existing equipment deterioration from vulnerabilities introduced through digital integration and software modifications. These measures support sustained instrumentation dependability throughout prolonged nuclear facility operation.

1.3. Safety Implications of Digital Control Upgrades

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Digital instrumentation and control (I&C) upgrades offer opportunities to enhance nuclear plant safety through improved monitoring accuracy, automated protection, and advanced diagnostic capabilities. However, replacing analogue systems with digital technologies introduces architectural complexities, software dependencies, and potential failure mechanisms requiring comprehensive safety assessment. Modernisation must therefore demonstrate that essential reactor protection, emergency shutdown, and engineered safety functions remain reliable across normal and abnormal operating conditions. Software-related common-because failures represent significant safety concerns because shared programming defects, development platforms, or communication dependencies can simultaneously compromise redundant protection channels. Systems-theoretic safety assessments highlight the importance of identifying hazardous interactions, preserving functional independence, and evaluating vulnerabilities that conventional redundancy arrangements may not adequately address (Bao, Shorthill & Zhang, 2020). Similarly, state-transition reliability modelling demonstrates how hardware failures, software abnormalities, and common-cause events influence reactor protection system availability (Shouman et al., 2021). Human-system integration presents additional challenges. Digital control rooms improve information accessibility and alarm management but may introduce cognitive overload, interface complexity, and procedural uncertainties. Consequently, human-factors evaluation, operator training, and interface validation remain essential for maintaining effective operational decision-making (Porthin, Liinasuo & Kling, 2020). Cybersecurity considerations further influence digital upgrade safety because interconnected controllers and communication networks introduce potential pathways for malicious interference. Research on cyber-physical resilience in digital substations demonstrates the importance of coordinated protection mechanisms, network segregation, and controlled system access (Shittu, Shittu & Olagunju, 2024). Hybrid protection architectures incorporating technological diversity may additionally reduce certain common-cause vulnerabilities, depending on system configurations and failure assumptions (Jeong, Son & Heo, 2021). Ultimately, dependable modernisation requires independent verification, configuration management, representative failure testing, and documented safety justification to ensure that digital enhancements preserve established nuclear protection requirements throughout operational service.

1.4. Review Objectives, Scope, and Methodology

This review critically examines the interrelationship between failure mode analysis, configuration management, and digital instrumentation and control modernization in ageing nuclear power plants. Its principal objective is to evaluate how technological upgrades influence system reliability, operational safety, and regulatory compliance while identifying engineering practices capable of mitigating emerging vulnerabilities. Particular attention is directed toward ageing-related degradation, equipment obsolescence, software-dependent failures, common-cause vulnerabilities, and the preservation of safety-critical functions throughout modernization activities. The review encompasses analogue-to-digital transitions, hybrid control architectures, reactor protection systems, monitoring infrastructure, and associated engineering interfaces. It further investigates the application of failure mode and effects analysis, fault-tree analysis, probabilistic safety assessment, and reliability-centered maintenance in evaluating equipment degradation and upgrade-related risks. Configuration management is examined through design documentation, baseline verification, software version control, change authorization, and lifecycle

traceability, emphasizing their contributions to maintaining consistency between installed equipment and approved safety requirements.

Methodologically, the study adopts a structured narrative literature review supported by comparative and thematic analysis of peer-reviewed publications, nuclear engineering research, regulatory guidance, and established technical standards published through 2025. Relevant literature is organized according to technological modernization, failure mechanisms, safety assurance, and implementation constraints. The synthesis evaluates convergent findings, methodological limitations, and unresolved engineering challenges without claiming independent experimental validation. Through this approach, the review establishes an analytical foundation for identifying practical improvement strategies, strengthening configuration integrity, and informing risk-sensitive modernization decisions in nuclear facilities undergoing extended operational service and continued technological transformation.

2. Digital Instrumentation and Control Modernization

2.1. Architecture of Nuclear Instrumentation and Control Systems

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Nuclear instrumentation and control (I&C) architectures provide the technological foundation for reactor monitoring, operational regulation, and safety protection. These systems integrate sensors, signal-conditioning equipment, digital processors, communication networks, and actuators to support coordinated plant operations. Their design incorporates functional independence, redundancy, diversity, and defence-in-depth to minimise potential failures affecting safety-related functions. International safety standards emphasise functional classification, environmental qualification, interface compatibility, and systematic verification throughout the system lifecycle (IAEA, 2016). Traditional nuclear facilities predominantly employ analogue instrumentation and hardwired control mechanisms, whereas modern architectures increasingly integrate programmable controllers, field-programmable gate arrays, and distributed digital platforms. Supervisory control and data acquisition technologies enhance operational visibility, equipment coordination, and information management, although interconnected automation introduces additional integration requirements (Omoegun et al., 2024). Digital neutron flux monitoring further demonstrates the potential of advanced processing technologies to strengthen reactor instrumentation while maintaining essential measurement reliability (Ibrahim et al., 2020).

Architectural modernisation additionally requires systematic evaluation of software dependencies, communication interfaces, and component interactions. Model-driven engineering frameworks support functional specification, architectural verification, and integration of safety and security requirements, enabling potential design inconsistencies to be identified before implementation (Ouni et al., 2021). Similarly, structured digital information models facilitate engineering coordination, equipment documentation, and configuration consistency across nuclear facility lifecycles (Shentu & Zheng, 2019). Reliability assessment remains essential when integrating new technologies with existing infrastructure. Experimental failure analysis and root-cause investigation provide complementary methods for identifying component vulnerabilities and informing corrective interventions (Akanbi, Ganiu & Sunday, 2023). However, redundant digital channels may remain susceptible to shared software defects and common-cause failures. Redundancy-guided hazard analysis therefore supports the identification of critical dependencies and appropriate architectural safeguards (Shorthill et al., 2022).

Ultimately, effective digital I&C modernisation requires validated interfaces, controlled software modifications, traceable engineering configurations, and demonstrable functional independence. These provisions are particularly important in ageing nuclear facilities where emerging technologies must coexist safely with retained instrumentation and established reactor protection arrangements.

2.2. Ageing Mechanisms and Equipment Obsolescence

Ageing nuclear instrumentation and control systems experience progressive deterioration arising from prolonged exposure to thermal stress, radiation, electrical loading, humidity, and operational cycling. These conditions can degrade semiconductor devices, sensing elements, connectors, and circuit assemblies, compromising measurement accuracy and protective functionality. Semiconductor investigations demonstrate how displacement-induced defects alter material characteristics and electronic performance, underscoring the importance of understanding degradation mechanisms when evaluating component reliability (Gideon & Erhimefe, 2025).

Equipment obsolescence introduces additional challenges because electronic components frequently become commercially unavailable before nuclear facilities complete their operational lifetimes. Consequently, replacement decisions must consider functional compatibility, environmental qualification, software dependencies, and configuration traceability. Research on programmable logic controller components indicates that temperature fluctuations and electrical stress significantly influence remaining useful life, supporting condition-informed replacement planning rather than reliance exclusively on nominal failure rates (Jang & Kim, 2024).

Experience from Ghana's research reactor demonstrates the practical consequences of ageing infrastructure. Refurbishment of control-system circuit boards, periodic equipment testing, and corrective maintenance were employed to address instrumentation deficiencies and preserve operational capabilities. These activities illustrate the importance of maintaining accurate equipment histories and implementing controlled modifications when original components deteriorate or become obsolete (Gasu et al., 2023).

Condition-monitoring technologies also contribute to early fault identification and maintenance prioritization. Vibration-based diagnostic approaches using LabVIEW demonstrate how continuous measurement, signal processing, and equipment-health assessment can support predictive maintenance and operational reliability (Omoegun et al., 2023). For nuclear modernization projects, such monitoring should complement systematic failure mode analysis, documented configuration baselines, and qualified replacement procedures. Integrating these practices enables engineers to distinguish progressive physical degradation from modification-induced faults while reducing the likelihood that obsolete equipment, undocumented interfaces, or incompatible replacement technologies will undermine safety-related system performance during extended plant operation.

2.3. Digital Retrofitting and System Integration Requirements

Digital retrofitting in ageing nuclear power plants requires coordinated replacement of obsolete instrumentation without compromising safety functions or approved design configurations. Modernization involves integrating programmable controllers, digital sensors, operator interfaces, and communication networks with retained analogue equipment. The principal engineering challenge lies in demonstrating functional compatibility while preserving system independence, deterministic response, and protection against common-cause failures. International industry guidance emphasizes that modernizing operating reactors introduces licensing, cybersecurity, and

architectural constraints that cannot be resolved through equipment substitution alone (World Nuclear Association, 2020).

Integration planning must begin with inventories of installed hardware, software, signal pathways, and interface requirements. Engineers should establish configuration baselines, characterize failure modes, and verify that replacement devices satisfy environmental, electromagnetic, and functional qualification criteria. Nigerian-associated research on blockchain-assisted SCADA communication highlights data integrity, interoperability, and secure information exchange as considerations in digitally connected control environments (Shittu et al., 2022).

Operational integration demands coordinated testing of automation logic, alarms, communication latency, and fallback arrangements. Research concerning modern electricity networks demonstrates the importance of automation management and real-time visibility when integrating distributed control functions (Shittu, Adaramola & Shittu, 2025). For nuclear applications, however, real-time control must remain within validated performance limits, with changes formally assessed before implementation.

Evidence from Ghana's research reactor illustrates the value of systematic reliability analysis during control-system development. Failure mode, effects, and criticality analysis identified vulnerable components and informed protective measures for a semiautomated monitoring arrangement (Obeng, Edziah & Amponsah-Abu, 2025). Accordingly, retrofit programmes require documented design reviews, independent verification, staged commissioning, and controlled software revisions. These activities should preserve traceability between safety requirements, installed configurations, test evidence, and maintenance records throughout plant operation.

3. Failure Mode Analysis and Risk Assessment

3.1. Hardware, Software, and Common-Cause Failure Mechanisms

Digital instrumentation and control (I&C) systems in ageing nuclear power plants are exposed to interrelated hardware, software, and common-cause failure mechanisms that can compromise protective functionality and operational reliability. Hardware failures arise from semiconductor degradation, insulation deterioration, unstable power supplies, defective interfaces, and environmental stress. Such abnormalities may produce inaccurate measurements, delayed protective actuation, or intermittent malfunctions. Sensor-based monitoring provides opportunities for early fault identification through systematic evaluation of operating parameters and abnormal equipment responses (Sunday & Omoegun, 2022).

Electrical faults represent another significant concern, particularly where ageing cables and replacement instrumentation coexist. Insulation breakdown, electromagnetic interference, and degraded connections can disrupt signals essential to protective operations. Research involving Egyptian nuclear research reactor infrastructure demonstrates the application of machine-learning techniques for detecting and locating electrical cable faults, highlighting the potential contribution of intelligent diagnostics to equipment reliability assessment (Saad & Said, 2023).

Software failures present distinct challenges because systematic defects may remain undetected during routine operation until particular input combinations or operating conditions activate them. Errors originating from incomplete specifications, defective algorithms, or inadequate verification can consequently undermine multiple control functions. Structured reliability demonstration frameworks emphasize traceable evidence connecting software requirements, development processes, and verification outcomes (Guo et al., 2018).

Quantifying software reliability is particularly challenging where operational failure data remain insufficient. Bayesian belief networks provide analytical mechanisms for incorporating

development quality, verification effectiveness, and uncertainty into software reliability estimates (Kang et al., 2018). Nevertheless, probabilistic estimates require careful interpretation because numerical outputs depend upon assumptions and available evidence.

Fault-tolerant architectures incorporate redundant processors, diagnostic routines, and voting arrangements to maintain essential functions despite individual component failures. Experimental fault-injection investigations demonstrate that their effectiveness depends on detection coverage, recovery capabilities, and implementation characteristics (Kim et al., 2019).

Common-cause failures are especially consequential because shared software defects, design assumptions, or dependencies can defeat nominally independent protection channels. Integrated reliability approaches incorporating human reliability assessment and common-cause failure modelling provide mechanisms for examining these vulnerabilities systematically (Shorthill et al., 2021). More recent intersystem investigations further demonstrate the importance of identifying coupling factors capable of propagating software failures across interconnected digital subsystems (Kim et al., 2024).

Table 1 illustrates representative failure mechanisms, their safety implications, and appropriate engineering controls applicable to digital I&C modernization.

Table 1. Illustrative Failure Modes and Engineering Controls for Digital I&C Upgrades

Failure category	Representative failure mode	Potential safety implication	Recommended engineering controls
Hardware degradation	Sensor drift, circuit deterioration, or power supply instability	Incorrect measurements or unavailable protection channels	Calibration, condition monitoring, environmental qualification
Electrical interface failure	Cable insulation breakdown, electromagnetic interference, or defective connections	Signal corruption or interrupted protective commands	Cable testing, shielding, interface verification
Software malfunction	Programming defects, logic errors, or unhandled operating states	Incorrect control decisions or failed protective actuation	Independent verification, regression testing, requirements traceability
Fault-tolerance failure	Undetected processor faults or ineffective diagnostic recovery	Reduced channel availability and impaired redundancy	Fault injection, diagnostic coverage assessment, recovery testing
Hardware common-cause failure	Shared power supply, cooling, or environmental vulnerability	Simultaneous impairment of redundant channels	Physical separation, independence assessment, diverse support arrangements
Software common-cause failure	Identical systematic defects across replicated applications	Concurrent failure of multiple protection channels	Software diversity assessment, independent development, hazard analysis
Configuration-induced failure	Incorrect firmware, undocumented parameter changes, or incompatible replacements	Unintended system behaviour following modification	Version control, approved configuration baselines, change authorization

Source: Author's synthesis of the failure mechanisms and engineering controls discussed in the seven references listed above. The table presents illustrative scenarios rather than measured plant-specific failure frequencies.

3.2. Failure Mode Analysis and Probabilistic Safety Assessment

Failure mode analysis and probabilistic safety assessment (PSA) provide complementary methodologies for evaluating the reliability of digital instrumentation and control systems in ageing nuclear power plants. Failure mode and effects analysis systematically identifies component malfunctions, evaluates their consequences, and establishes preventive measures. Integrating reliability-centered maintenance with structured process improvement supports the prioritization of critical equipment and risk-informed interventions (Olutimehin & Ganiu, 2022).

Statistical process control complements failure analysis by identifying abnormal variability, emerging equipment deterioration, and departures from established operating limits. Control charts and process capability evaluations provide quantitative evidence for maintenance decisions and performance monitoring (Akanbi, Ganiu & Sunday, 2022). However, these techniques require appropriate measurement validation before application to safety-critical nuclear instrumentation.

PSA extends component-level investigations by quantifying accident sequences through fault-tree analysis, event-tree modelling, and uncertainty assessment. Its application to digital I&C supports risk-informed surveillance, quality assurance, and system design decisions, particularly where component dependencies influence protective functionality (Lu & Jiang, 2004).

African nuclear engineering research demonstrates the practical application of these methodologies. A Ghanaian investigation employed fault-tree and event-tree techniques to estimate core damage frequency associated with flow blockage and loss-of-coolant scenarios, illustrating the importance of evaluating protective system dependability under postulated accidents (Ameyaw et al., 2021). Digital reactor protection introduces additional analytical complexities involving software failures, diagnostic coverage, redundancy, and common-cause vulnerabilities. A Chinese reliability assessment identified undetected common-cause failures in signal-conditioning modules as significant contributors to reactor protection unavailability (Liang et al., 2020). Accordingly, credible modernization assessments require verified failure assumptions, documented configuration baselines, sensitivity analysis, and systematic consideration of uncertainties when evaluating replacement technologies and associated safety margins throughout extended nuclear plant operation.

4. Configuration Management and Safety Assurance

4.1. Configuration Baselines, Traceability, and Change Control

Configuration management is fundamental to maintaining design integrity and operational safety during digital instrumentation and control upgrades in ageing nuclear power plants. It establishes controlled relationships among approved design requirements, installed equipment, software configurations, and operational documentation. Without these relationships, equipment replacement may introduce discrepancies between intended functionality and actual plant conditions. International nuclear guidance identifies configuration consistency as essential for ensuring that physical installations, documented requirements, and operating arrangements remain aligned throughout facility lifecycles (IAEA, 2010). Configuration baselines establish authoritative reference states against which proposed modifications can be evaluated. These baselines encompass hardware specifications, software versions, interface definitions, engineering drawings, and safety classifications. Historical investigations into nuclear plant configuration management demonstrate the value of reconstructing design information and integrating technical records into structured information systems, particularly where legacy documentation is incomplete or inconsistent (Smith & Cook, 1990).

Traceability provides verifiable connections between safety requirements, engineering decisions, implementation activities, and acceptance testing. For digital upgrades, traceability matrices should connect each requirement to corresponding software modules, hardware interfaces, verification procedures, and documented results. Canadian nuclear engineering research emphasizes the importance of software classification, qualification, and quality assurance when replacing obsolete equipment or introducing embedded firmware during plant life-extension projects (LeReverend, 2019). Effective change control requires formal authorization before modifications are implemented. Proposed changes should undergo technical evaluation, safety impact assessment, independent review, and configuration documentation updates. Canadian regulatory guidance identifies design change tracking, preservation of safety information, and configuration management across operational stages as essential engineering responsibilities (CNSC, 2014). Governance arrangements reinforce these technical processes by establishing accountability and documented approval responsibilities. Nigerian research examining IT governance frameworks highlights the contributions of structured oversight, auditability, and compliance monitoring to organizational control (Fadero et al., 2018). Similarly, enterprise governance research emphasizes transparent decision-making, defined responsibilities, and integrated performance oversight as mechanisms for reducing organizational inconsistencies (Akhigbe, Falemi & Akin-Oluyomi, 2025). African nuclear regulatory development further illustrates the significance of configuration integrity. Ghana's draft nuclear installation regulations address design requirements, controlled modifications, technical documentation, and responsibilities for maintaining safety throughout facility operation (NRA, 2024).

Table 2 presents an illustrative configuration management framework applicable to nuclear digital modernization programmes.

Table 2. Configuration Management Controls for Digital I&C Upgrades

Configuration element	Principal risk	Required management control	Verification evidence
Design requirements	Inconsistent safety specifications	Approved design baseline	Design review records
Hardware configuration	Incompatible replacement components	Equipment identification and qualification	Inspection and test reports
Software configuration	Unauthorized code or firmware changes	Version control and release authorization	Software revision records
Interface specifications	Communication or signal incompatibility	Interface control documentation	Integration test results
Requirements traceability	Unverified safety functionality	Requirements-to-test mapping	Traceability matrix
Engineering modifications	Unassessed safety consequences	Formal modification approval	Safety evaluation records
Operational documentation	Discrepancies between records and installations	Controlled document revision	Updated drawings and procedures

Source: Author's synthesis of configuration management principles and nuclear engineering requirements discussed in the seven references above.

These controls provide a structured basis for identifying configuration discrepancies, preserving technical accountability, and ensuring that approved modifications remain consistent with established nuclear safety requirements. Effective implementation also requires periodic configuration audits, independent verification, and retention of auditable records throughout successive modernization activities.

4.2. Verification, Validation, and Regulatory Compliance

Verification and validation constitute essential elements of safety assurance during digital instrumentation and control (I&C) upgrades in ageing nuclear power plants. Verification determines whether hardware, software, and system designs satisfy specified engineering requirements, whereas validation establishes whether integrated equipment performs its intended functions under representative operating conditions. Both activities require documented acceptance criteria, independent technical assessment, and traceable evidence linking approved specifications to installed configurations. Reliable verification begins with requirements analysis and proceeds through design reviews, component testing, software examination, and integrated functional assessment. Investigations into electrical load optimization illustrate the importance of evaluating system performance against defined operational constraints and reliability expectations (Sunday & Omoegun, 2019). Within nuclear applications, these principles must incorporate protective actuation requirements, channel independence, and qualified environmental conditions. Digital protection equipment introduces challenges associated with embedded software, programmable logic, and interconnected components. Formal model checking can identify unintended system behaviour that conventional testing may overlook. Finnish nuclear engineering research demonstrated that systematic examination of application logic can expose design inconsistencies capable of producing spurious protective actuation (Pakonen, Buzhinsky & Björkman, 2021). Hardware verification must additionally establish dependable fault detection and response. Research involving field-programmable gate arrays demonstrated how built-in self-testing can improve diagnostic coverage in safety-critical reactor control arrangements (Lin et al., 2022). Such techniques should complement independent testing rather than substitute for comprehensive qualification. African research contributes perspectives concerning monitoring integrity and functional dependability. An Egyptian investigation of fault-tolerant radiation monitoring examined sensor validation and networked monitoring arrangements, emphasizing reliable measurement acquisition under abnormal conditions (Habash, Ayad & Ammar, 2021). These considerations are important when existing instrumentation interfaces with newly installed digital systems. Power quality and electromagnetic compatibility also influence verification activities. Nigerian-associated research on harmonic mitigation demonstrates how intelligent monitoring and control algorithms can evaluate disturbances in electrical distribution networks (Adeniji et al., 2025). Nuclear installations must additionally verify that electrical interference and abnormal supply conditions cannot compromise credited safety functions.

Emerging artificial intelligence applications introduce further verification difficulties because adaptive behaviour, training-data limitations, and model uncertainty complicate conventional testing. A dedicated verification strategy for nuclear I&C artificial intelligence components emphasizes systematic process assessment and functional testing tailored to these technologies (Park, Kim & Koo, 2023). Regulatory compliance requires evidence that verification activities extend throughout equipment development, installation, commissioning, and maintenance. International regulatory consensus highlights inspection planning, quality management, and evaluation of digital hardware and software against their intended safety functions (OECD NEA,

2025). Consequently, operators should maintain approved test procedures, configuration baselines, nonconformance records, and documented corrective actions. Licensing evidence must demonstrate that modifications preserve applicable safety requirements, with regulatory approval obtained where required before upgraded equipment enters service.

Table 3. Illustrative Verification, Validation, and Regulatory Compliance Framework for Digital I&C Upgrades

Assessment area	Principal verification or validation activity	Required evidence	Safety and compliance objective
System requirements	Verify functional and safety specifications against the approved design basis.	Requirements traceability matrix	Confirm completeness and consistency
Software assurance	Conduct code reviews, static analysis, formal verification, and regression testing.	Review reports and test records	Identify systematic software defects
Hardware qualification	Evaluate environmental tolerance, electrical compatibility, and diagnostic functionality.	Qualification and test certificates	Demonstrate dependable equipment operation
Integrated system validation	Test control logic, interfaces, protective actuation, and abnormal operating scenarios	Integration and acceptance test reports	Establish intended functional performance
Fault tolerance	Examine redundant channels, diagnostics, and common-cause vulnerabilities	Fault-injection results and failure analyses	Preserve protection-system dependability
Configuration control	Verify installed hardware, software versions, and approved parameter settings.	Configuration audit records	Prevent unauthorized or incompatible modifications
Regulatory compliance	Review licensing commitments, safety assessments, and inspection findings	Safety evaluation and regulatory submission records	Demonstrate conformity with applicable regulatory requirements

Source: Author's synthesis of verification, validation, and compliance principles examined in the seven references above. The framework is illustrative; actual acceptance criteria depend on the facility's licensing basis and applicable national regulations.

5. Implementation Challenges and Future Research Directions

5.1. Legacy System Compatibility and Cybersecurity Vulnerabilities

Digital instrumentation and control (I&C) modernisation in ageing nuclear facilities presents significant challenges involving legacy system compatibility, technological integration, and cybersecurity vulnerabilities. Existing nuclear infrastructure frequently incorporates analogue instrumentation, proprietary communication protocols, and control architectures developed before

contemporary digital security requirements. Integrating modern technologies therefore necessitates careful evaluation of interface compatibility, signal integrity, communication latency, and functional independence. Effective systems integration depends on coherent information architectures and reliable communication mechanisms that preserve operational stability (Pokane, Shilenge & Telukdarie, 2022). Compatibility challenges become particularly pronounced when digital platforms interact with ageing sensors, actuators, and protection circuits. Inconsistent data formats, undocumented interfaces, and processing differences may compromise system reliability and complicate fault identification. Digital twin technologies offer opportunities for integrating equipment measurements, virtual representations, and diagnostic capabilities, although their effectiveness requires validated interfaces and dependable information exchange (Shittu et al., 2023). Cybersecurity vulnerabilities further complicate modernisation as interconnected control networks introduce potential pathways for unauthorised access, malicious software, and operational disruption. Nuclear cybersecurity assessments emphasise the importance of protecting digital infrastructure against threats capable of compromising system availability and operational integrity (Ayodeji et al., 2023). Consequently, security evaluation must consider cyber-physical dependencies, communication boundaries, and potential consequences for reactor safety (Busquim e Silva et al., 2021). Effective protection requires layered cybersecurity mechanisms incorporating access restrictions, network segmentation, intrusion monitoring, and controlled software modifications. Attribute-based encryption provides complementary mechanisms for protecting sensitive engineering information through defined authorisation policies (Shittu & Nabil, 2023). Similarly, structured attack-pattern analysis supports vulnerability identification, threat prioritisation, and verification of implemented safeguards (Lee, Kwon & Yoon, 2022).

International technical guidance reinforces the importance of security modelling, architectural separation, and systematic interface assessment within nuclear digital systems (IEC, 2023). Future research should prioritise secure legacy integration, interoperable communication frameworks, and validated cyber-physical resilience mechanisms. Integrating these approaches with configuration management and safety verification remains essential for maintaining dependable nuclear operations throughout digital modernisation.

5.2. Predictive Diagnostics and Risk-Informed Modernization Strategies

Predictive diagnostics and risk-informed modernisation strategies provide opportunities to enhance the reliability, maintainability, and operational safety of ageing nuclear instrumentation and control (I&C) systems. Unlike conventional maintenance practices relying on scheduled inspections or corrective interventions, predictive approaches utilise operational measurements, degradation indicators, and analytical models to identify emerging equipment abnormalities. Prognostics and health management frameworks integrate condition monitoring, fault diagnosis, remaining-useful-life estimation, and maintenance planning to support proactive asset management and informed engineering decisions (Zhao et al., 2021).

Machine-learning techniques have demonstrated potential for detecting abnormal operating conditions and identifying developing equipment faults. Research involving artificial neural networks and nuclear plant simulations illustrates how intelligent diagnostic models can distinguish fault conditions during operational transients, supporting condition-dependent maintenance strategies (Ayo-Imoru & Cilliers, 2018). However, diagnostic reliability depends on representative training datasets, measurement accuracy, and appropriate model validation.

Digital twin technologies offer complementary capabilities by integrating physical equipment representations with operational measurements and computational models. Artificial intelligence-

enabled digital frameworks demonstrate potential for fault prediction, equipment monitoring, and maintenance optimisation within energy infrastructure (Shittu & Shittu, 2024). Physics-informed digital twins further support fault isolation by comparing observed equipment behaviour with expected system responses, potentially improving diagnostic accuracy under uncertain operating conditions (Nguyen et al., 2022). Data-driven condition assessment additionally facilitates anomaly detection, fault classification, and equipment degradation forecasting. Nevertheless, limited failure records, changing operating conditions, and measurement uncertainties constrain model generalisability, particularly within safety-critical nuclear environments (Xu, Cai & Song, 2022).

Risk-informed modernisation must consequently integrate predictive evidence with component criticality, failure consequences, maintenance requirements, and regulatory obligations. Prognostics-based maintenance frameworks emphasise the importance of coordinating intervention timing with operational dependencies and equipment reliability (Xiao et al., 2023). Future research should prioritise interpretable diagnostic models, validated digital twins, uncertainty quantification, and integration with probabilistic safety assessment. These developments can support evidence-based equipment replacement while preserving functional independence, configuration integrity, and established nuclear safety requirements.

Conclusion

This review examined how ageing-related deterioration, digital failure mechanisms, and configuration management interact to influence the safety and reliability of nuclear instrumentation and control systems. Its objectives were addressed through a synthesis of literature on system architecture, equipment obsolescence, failure assessment, safety assurance, and modernization constraints. The analysis establishes that replacing analogue equipment with digital technology can strengthen diagnostic capability and operational visibility, but technological advancement alone does not guarantee improved protection performance.

A principal finding is that ageing infrastructure presents interconnected challenges. Component degradation, unavailable spare parts, incomplete design records, and incompatible interfaces can undermine upgrade effectiveness. Moreover, digital platforms introduce systematic software defects, shared dependencies, cybersecurity exposure, and common-cause failure pathways that may defeat redundant protection channels. Failure mode and effects analysis, fault-tree analysis, and probabilistic safety assessment therefore provide complementary means of identifying vulnerabilities, examining accident sequences, and prioritizing risk reduction. Their usefulness depends on defensible assumptions, validated evidence, and treatment of uncertainty.

The review also demonstrates that configuration management is integral to safety rather than merely administrative documentation. Approved baselines, requirements traceability, controlled software releases, and modification authorization enable engineers to relate the installed plant to its design basis. Independent verification, integrated testing, and regulatory engagement are indispensable when legacy and replacement systems operate together. Predictive diagnostics and digital twins offer maintenance support, although their outputs require qualification before influencing safety-related decisions.

Accordingly, plant operators should adopt phased modernization programmes grounded in equipment criticality and plant-specific risk assessments. Priorities should include configuration audits, common-cause failure evaluations, cybersecurity segregation, fault-injection testing, and preservation of auditable engineering records. Regulators and researchers should further develop evidence-based approaches for assessing software reliability, diagnostic uncertainty, and long-

term digital obsolescence. These measures can support safer extended operation while ensuring that modernization decisions remain transparent, technically justified, and consistent with nuclear safety obligations.

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