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A Life-Cycle Regulatory Inspection Framework for Light-Water Small Modular Reactors

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1. Introduction

Small modular reactors (SMRs) are increasingly being developed as an alternative pathway for expanding nuclear energy deployment through smaller unit capacities, modular construction, factory-based manufacturing, and standardized production. In particular, light-water SMRs (LW-SMRs) differ materially from conventional large pressurized-water reactors (PWRs) in their design characteristics, construction methods, operating concepts, and safety cases. Many LW-SMR designs integrate major primary-system components within a compact reactor vessel, employ passive safety functions for heat removal and accident mitigation, provide extended fuel cycles or long refuelling intervals, and are designed for multi-module deployment using standard factory-fabricated modules. At the same time, their instrumentation and control (I&C) systems and control rooms are increasingly digitalized. These characteristics can reduce construction time, improve manufacturing consistency, and enhance standardization, but they also fundamentally alter how and where safety-significant evidence is generated and verified.

For conventional large PWRs, regulatory inspection has traditionally been centered on activities performed at the nuclear site, including construction, installation, system functional testing, commissioning, and operational verification. In LW-SMRs, however, a portion of safety-significant evidence may be generated before a module reaches the nuclear site. Manufacturing processes, supplier quality assurance, factory acceptance testing, module transportation, and configuration control can directly affect the safety performance of the completed plant. In addition, the safety of an SMR plant cannot always be demonstrated solely through verification of individual modules. The performance of passive safety functions, the interfaces between modules, shared systems, common support systems, and integrated digital I&C architectures must also be demonstrated under representative plant conditions. Consequently, an inspection framework designed primarily for site-built, single-unit large PWRs may leave regulatory gaps during the pre-site manufacturing stage while providing insufficiently explicit requirements for integrated and multi-module verification [1–3].

These characteristics have important implications for the regulatory inspection framework. The regulatory focus must extend beyond conventional construction inspection toward the entire chain of manufacturing, transportation, site assembly, integrated commissioning, operation, and eventual decommissioning. In particular, inspection should provide sufficient regulatory assurance that safety-significant manufacturing activities are performed under controlled conditions, that transported modules retain their required structural and functional integrity that site assembly correctly reproduces the approved configuration, and that integrated plant functions satisfy their specified safety and performance requirements. This requires a transition from a predominantly site-centered inspection model toward a life-cycle-based inspection framework in which safety evidence is generated, verified, documented, and transferred across successive stages of the SMR life cycle.

This issue is faced directly as it advances the development and regulatory preparation of the innovative SMR (i-SMR). The regulatory system has been established through the Nuclear Safety Act and associated technical standards, regulations, notices, and inspection procedures, most of which have evolved around large commercial light-water reactors constructed and commissioned at fixed nuclear sites. This issue is becoming increasingly important as the development and regulatory preparation of innovative SMRs (i-SMRs) advance. The current regulatory framework is based on the Nuclear Safety Act and associated technical standards, regulations, notices, and inspection procedures. However, most of these requirements were originally developed for large commercial light-water reactors that are constructed and operated at fixed nuclear sites.

While the fundamental principles of this regulatory framework still apply to SMRs, the distinct design and delivery characteristics of LW-SMRs raise questions regarding the timing, scope, and depth of regulatory inspection. In particular, factory acceptance testing, manufacturing-process verification, transportation-condition verification, module-to-module interfaces, shared-system performance, passive safety-system testing, digital I&C verification, and integrated multi-module testing are not necessarily addressed with the

same specificity as comparable activities for conventional large PWRs.

The issue is therefore not whether the existing regulatory framework should be replaced by a completely new SMR-specific system. Rather, the key question is how the existing framework can be adapted and extended so that its legal and institutional continuity is maintained while its inspection requirements become responsive to the technical characteristics and risk significance of LW-SMRs. Such adaptation is particularly important because excessive reliance on prescriptive requirements developed for large PWRs could result in unnecessary regulatory burdens, whereas insufficiently specified requirements could leave important safety functions and interfaces inadequately verified.

Against this background, this study addresses the central research question of how to adapt its existing regulatory inspection framework to accommodate the distinctive design and life-cycle characteristics of LW-SMRs while maintaining legal and institutional coherence. The study evaluates the applicability of the current inspection framework across the major stages of the LW-SMR life cycle and systematically identifies regulatory inspection gaps arising from the differences between conventional large light-water reactors and SMR technologies. The analysis covers the principal life-cycle stages, including manufacturing, transportation, site assembly, pre-operational testing, commissioning, operation, and decommissioning. Particular attention is given to technical areas that present new or enhanced inspection challenges for LW-SMRs, including passive safety systems, multi-module and shared-system configurations, digital instrumentation and control (I&C), risk-significant non-safety structures, systems, and components (SSCs), factory fabrication, supply-chain quality assurance (QA), and first-of-a-kind (FOAK) design verification. Through this life-cycle assessment, the study aims to identify where existing inspection requirements remain applicable, where they require supplementation, and where new inspection criteria or regulatory mechanisms are necessary to establish an effective, graded, and risk-informed inspection framework for future LW-SMR deployment.

The study is based on the findings of a two-year research program and reconstructs those findings into an integrated inspection framework. The research pursues three specific objectives. First, it identifies and characterizes life-cycle inspection gaps that may arise when the existing inspection guidance is applied to LW-SMRs. Second, it prioritizes these gaps according to technical area, life-cycle stage, safety significance, and the degree of modification required to the existing inspection framework. Third, it proposes practical regulatory and technical measures for establishing a risk-informed and importance-graded inspection system that can be implemented within the existing regulatory structure.

The principal contribution of this study is the development of an inspection framework that connects factory oversight, site assembly inspection, integrated commissioning, operational inspection, and decommissioning verification within a single life-cycle framework. Rather than adding inspection items, the new approach defines verification steps between each lifecycle stage. It also incorporates graded inspection principles to tailor inspection scope and rigor according to the safety significance of SSCs and functions, while providing additional regulatory attention to passive safety functions and non-safety SSCs subject to Regulatory Treatment of Non-Safety Systems (RTNSS).

Through this approach, the study aims to establish a practical inspection framework that builds on the existing regulatory inspection system while accommodating the distinctive characteristics of future i-SMR deployment.

The proposed framework is intended not to replace the established licensing structure, but to enhance its technical responsiveness by extending regulatory inspection to the locations and stages where safety-significant evidence is actually generated. In this respect, the study provides a basis for developing SMR-specific inspection criteria and procedures in advance of i-SMR standard-design approval and subsequent deployment, while maintaining consistency with established nuclear safety regulatory principles.

2. Methodology and Analytical Scope

The study used a three-step gap-analysis method. First, applicable regulatory inspection topics and guidance were mapped to the SMR life cycle: design, factory fabrication, transport, site assembly, pre-operational testing, operation, and decommissioning. Second, the mapped topics were compared with representative international practices and reference documents, including U.S. requirements for construction and operational verification, risk-informed SSC categorization, quality assurance, emergency preparedness, and advanced-reactor review guidance; Canadian SMR pre-licensing information; UK safety assessment principles; and IAEA safety publications [4–12]. Third, each item was classified as directly applicable, applicable with supplementation, or requiring a new criterion. Priorities were set by taking account of safety and regulatory considerations, as well as whether important safety functions could be compromised.

This study adopts a three-step, life-cycle-based gap-analysis methodology to assess the adequacy of existing regulatory inspection framework for LW-SMRs. The methodology treats regulatory inspection as an integrated assurance function extending across the entire SMR life cycle, rather than as a collection of

independent field inspection activities. This approach reflects the distinctive characteristics of LW-SMRs, for which safety-significant evidence may be generated at different locations and stages, including the design organization, supplier and manufacturing facilities, transportation process, nuclear site, testing facilities, simulators, and operational reliability-monitoring programs.

2.1 Life-Cycle Mapping of the Inspection Framework

The first step was to map applicable regulatory inspection requirements, guidance, and inspection practices against the major life-cycle stages of the LW-SMR. The life-cycle framework comprises design, factory fabrication, transportation, site assembly and installation, pre-operational testing and commissioning, operation, and decommissioning. In addition, cross-cutting regulatory functions, including quality assurance, supplier inspection, configuration management, emergency preparedness, and operational reliability monitoring, were incorporated into the mapping framework.

The purpose of this mapping was to determine whether existing inspection requirements adequately cover the locations, activities, and safety evidence associated with each stage of the LW-SMR life cycle. Particular attention was given to inspection activities that are more significant for SMRs than for conventional large PWRs, including factory acceptance and manufacturing inspections, transportation-condition verification, module interface and assembly inspections, integrated commissioning tests, passive safety-system performance verification, digital instrumentation and control (I&C) verification, and multi-module and shared-system testing.

The practical inspection scope therefore encompasses pre-service inspection, periodic inspection, supplier inspection, quality-assurance inspection, staged module installation and commissioning, operational reliability verification, emergency-planning review, and decommissioning verification. This ensures that the analysis addresses the complete regulatory inspection life cycle rather than focusing on a single licensing or construction milestone.

2.2 Classification of Inspection Gaps

The third step classified each inspection topic according to its degree of applicability to LW-SMRs. Each item was assigned to one of three categories:

- Directly applicable: the existing inspection requirement can be applied to the corresponding SMR activity without substantive modification;
- Applicable with supplementation: the existing requirement remains fundamentally applicable but requires additional criteria, procedures, or verification methods to address SMR-specific characteristics; or
- New criterion required: the existing framework does not adequately address the activity or risk, requiring the development of a new SMR-specific inspection criterion or regulatory mechanism.

Following this classification, inspection gaps were prioritized qualitatively according to three principal factors: safety significance, regulatory urgency, and the potential loss or degradation of safety evidence if inspection is delayed until a later life-cycle stage. The third factor is particularly important for LW-SMRs because certain manufacturing and assembly activities cannot be meaningfully reconstructed or independently verified after a module has been completed, transported, installed, or enclosed within the plant.

Accordingly, inspection priority was assigned not only based on the potential safety consequence of an SSC or activity, but also based on when reliable regulatory evidence must be obtained. This principle allows the methodology to identify inspection hold points at stages where regulatory verification provides the greatest assurance and where subsequent verification may be technically difficult, costly, or impossible.

3. LW-SMR Characteristics Relevant to Inspection

LW-SMRs introduce a range of distinctive design and deployment characteristics that have direct implications for the scope, timing, methodology, and overall philosophy of regulatory inspection. In conventional large light-water reactors, most safety-related construction, installation, testing, and verification activities are performed at the nuclear site, and the regulatory inspection framework has consequently evolved around site-based construction and commissioning activities. In contrast, LW-SMRs rely extensively on factory fabrication, modular assembly, transportation of completed or partially completed modules, passive safety functions, multi-module configurations, and highly digitalized instrumentation and control systems. As a result, a substantial portion of safety-significant activities and associated regulatory evidence may be generated before the modules are delivered to the nuclear site.

These characteristics require a corresponding expansion of the regulatory inspection framework. Factory manufacturing processes, supplier quality assurance, module transportation, configuration control, and factory acceptance testing may become important elements of safety verification, while passive safety systems require inspection approaches capable of demonstrating functional performance and validating the assumptions underlying their analytical and experimental bases. Similarly, multi-module configurations introduce additional inspection requirements related to module interfaces, shared systems, common-cause failures, and integrated plant performance. The increasing use of digital I&C systems also requires regulatory attention to software verification and validation, cybersecurity,

configuration management, and human–machine interfaces.

Accordingly, the distinctive characteristics of LW-SMRs do not reduce the need for regulatory inspection; rather, they redistribute the location, timing, and nature of the safety evidence that must be generated and verified throughout the plant life cycle. Regulatory inspection must therefore extend beyond conventional site-based construction and commissioning activities to include manufacturing, supply-chain activities, transportation, module assembly, integrated testing, operational reliability, and decommissioning. This requires a transition from a predominantly site-centered inspection model toward a life-cycle-based, risk-informed, and evidence-oriented inspection framework that ensures the continued validity of design assumptions from manufacturing through operation.

Table 1 summarizes the principal design and deployment characteristics of LW-SMRs and their corresponding implications for regulatory inspection. The table is used as the basis for the subsequent assessment of the applicability of the existing inspection framework and the identification of SMR-specific inspection gaps.

One of the most significant changes is the increased reliance on factory fabrication and modular construction. Major reactor and safety-related modules may be manufactured, assembled, inspected, and tested before being transported to the nuclear site. Consequently, regulatory oversight including inspection, evaluation and enforcement limited primarily to site construction and installation would occur too late to verify a number of safety-significant manufacturing activities. Inspection must therefore extend upstream into manufacturing facilities and the supply chain, with particular attention to material control, special processes, welding and joining, dimensional tolerances, nondestructive examination (NDE), cleanliness, configuration control, quality assurance, factory acceptance testing, and preservation during transportation. The regulatory objective is not simply to inspect the completed module, but to establish traceable evidence that the manufacturing processes and acceptance activities have preserved the assumptions and requirements established in the approved design.

A second major characteristic is the extensive reliance on passive safety systems. In conventional reactors, safety-system verification has often relied on repeated actuation and functional testing of active components. Passive systems, by contrast, may depend on natural circulation, gravity, pressure differentials, heat transfer, condensation, or other inherent physical phenomena. Their safety performance therefore cannot always be demonstrated through conventional component-level actuation tests. Regulatory inspection should consequently emphasize functional demonstration, scaling and similarity assessment, validation of analytical models, verification of component and material conditions, instrumentation adequacy, uncertainty management, and long-term reliability monitoring. For example, the regulatory verification of a passive residual-heat-removal function should establish a continuous chain of evidence linking the as-built configuration and material condition to the experimental or test basis, analytical models, applicable scaling relationships, uncertainty treatment, and subsequent operational performance.

A related issue arises from alternative approaches to reactivity control, including boron-free or reduced-boron reactor concepts. Where soluble boron is reduced or eliminated, greater reliance may be placed on control rods, burnable absorbers, inherent feedback mechanisms, or other reactivity-control features. Such configurations can alter the inspection basis for shutdown margin, reactivity coefficients, control-system performance, fuel management, and accident response. The inspection framework should therefore be sufficiently technology-responsive to verify that the physical and analytical assumptions underlying reactivity control remain valid throughout manufacturing, commissioning, and operation.

A third major challenge is multi-module deployment and the associated dependence on shared systems. The safety assessment of an SMR plant cannot necessarily be reduced to the independent verification of each reactor module. Multiple modules may share electrical power, cooling systems, support systems, instrumentation and control functions, radioactive waste systems, emergency response resources, or other infrastructure. This creates potential interactions involving common-cause failure, shared-system capacity, isolation capability, maintenance configurations, system dependencies, and simultaneous operational states. Inspection must therefore examine both the performance of individual modules and the integrated behavior of the plant. Particular attention should be given to whether shared systems retain adequate capacity and functional independence under combinations of module operation, maintenance, abnormal conditions, and accident scenarios.

Multi-module operation also introduces inspection considerations that extend beyond conventional single-unit safety verification. These include the potential for aggregate source terms, simultaneous or cascading events, module-to-module interactions, common-cause failures, and concurrent operating and shutdown conditions. Emergency preparedness inspection must consequently consider not only the response to an event in a single module but also the potential consequences of events affecting multiple modules and the adequacy of common emergency support functions.

A fourth characteristic is the increasing reliance on digital instrumentation and control (I&C) systems and

highly automated control rooms. Digital platforms introduce inspection needs that differ from conventional hardware-based systems. Software verification and validation, configuration management, independence and segregation, cybersecurity, common-cause failure assessment, human–machine interfaces, and integrated human factors engineering become important components of the regulatory inspection basis. Inspection should therefore extend beyond individual equipment checks to include verification that software, hardware, communication interfaces, control-room functions, and operator actions operate consistently with the assumptions used in the safety analysis.

Taken together, these characteristics demonstrate that LW-SMR inspection should not be organized solely around physical installation status or deterministic safety classification. Instead, inspection should be sensitive to where safety is generated, where safety evidence is created, and where the validity of safety assumptions can be most effectively demonstrated. For LW-SMRs, this may involve a manufacturing facility, a module interface, a passive heat-removal function, a shared support system, a digital control platform, or an operational reliability-monitoring program. The inspection framework must therefore connect design requirements and safety assumptions with evidence generated at each stage of the plant life cycle.

This perspective also changes the role of regulatory inspection from a predominantly compliance-oriented activity toward an evidence-based verification process. For example, verification of a passive residual-heat-removal function should not be limited to confirming that individual components meet their specified requirements. Similarly, inspection of a shared electrical or cooling system should address not only the performance of individual components but also overall capacity, system dependencies, isolation capability, maintenance configurations, protection against common-cause failures, and the effects of simultaneous operation across multiple modules.

Accordingly, the distinctive characteristics of LW-SMRs require a transition from a site-centered and component-oriented inspection model toward a life-cycle-based and risk-informed inspection framework. The principal relationship between major LW-SMR characteristics and their resulting inspection implications is summarized in Table 2. The table provides the analytical basis for subsequently identifying specific inspection gaps and determining whether existing inspection requirements can be applied directly, require supplementation, or require the development of new SMR-specific criteria. Figure 1 illustrates the distribution of the identified inspection gaps across the major inspection domains

4. Regulatory Inspection Gaps for LW-SMR

The gap analysis indicates a substantial mismatch between the existing regulatory inspection framework and the technical and deployment characteristics of LW-SMRs. The issue is not the absence of an established regulatory basis for nuclear safety inspection, but rather that many existing inspection requirements were developed primarily for conventional large PWRs, where safety-significant manufacturing, installation, testing, and verification activities are largely performed at the nuclear site. In contrast, the modular and factory-based production model of LW-SMRs shifts a significant portion of these activities to manufacturing facilities and other stages of the supply chain that may not be subject to the same level of direct regulatory inspection. Consequently, the existing inspection framework may provide insufficient regulatory visibility and opportunities for independent verification of certain safety-significant activities before modules are transported to and incorporated into the nuclear site.

These characteristics indicate that the inspection framework for LW-SMRs should evolve from a predominantly site-centered and component-oriented approach toward a life-cycle-based, risk-informed, performance- and evidence-oriented approach. In particular, regulatory attention should extend across the major stages of the SMR life cycle, including factory fabrication, transportation, site assembly, commissioning, operation, and decommissioning. At the same time, the existing inspection framework should remain the fundamental regulatory basis, while SMR-specific inspection requirements and regulatory hold points should be introduced where existing provisions are insufficient. Particular attention is required for factory manufacturing and configuration control, multi-module and shared-system interfaces, passive safety functions, digital I&C and cybersecurity, FOAK technologies, and risk-significant non-safety systems.

Accordingly, the objective is not to replace the existing inspection system, but to extend and enhance it in a graded and risk-informed manner so that regulatory inspection activity is aligned with where safety-significant evidence is generated throughout the SMR life cycle. Such an approach would maintain regulatory continuity while providing the flexibility and verification capability necessary to support the standard design approval and eventual deployment of i-SMRs.

4.1 Factory Fabrication and Manufacturing Oversight

The most immediate regulatory gap concerns factory fabrication and manufacturing-stage inspection. Conventional nuclear inspection arrangements generally place substantial regulatory emphasis on activities performed following the installation of SSCs at the nuclear site. In contrast, LW-SMRs may involve the fabrication and partial or complete assembly of safety-significant modules at specialized manufacturing facilities before

transportation to the site. Critical activities such as welding, nondestructive examination, material verification, dimensional control, cleanliness control, assembly, pressure testing, and factory acceptance testing may therefore be completed before the module enters the conventional site-based inspection regime.

This creates a potential regulatory evidence gap. Once a module has been sealed, transported, or incorporated into the plant, certain manufacturing activities may be difficult or impossible to independently reproduce or inspect. Consequently, a regulatory framework that does not establish an appropriate basis for manufacturing-stage oversight may rely excessively on documentation generated by the licensee or supplier without providing sufficient opportunities for direct regulatory verification.

The implication is that the inspection framework should establish a clear mechanism for regulatory supervision of safety-significant manufacturing activities, including defined inspection hold points, supplier inspection requirements, factory acceptance criteria, quality-assurance verification, configuration control, and traceability of manufacturing records. Such oversight should be risk-informed so that regulatory resources are concentrated on manufacturing processes and SSCs whose failure could have significant safety consequences.

4.2 Multi-Module Configuration and Shared-System Interfaces

A second major gap concerns the inspection of multi-module configurations and shared systems. Conventional large-reactor inspection frameworks are predominantly organized around the verification of a single reactor unit and its associated systems. LW-SMR plants, however, may consist of multiple reactor modules that operate independently in some functions while relying on shared electrical, cooling, support, instrumentation and control, or emergency systems in others.

This configuration creates inspection issues that cannot be adequately addressed through module-by-module verification alone. Regulatory inspection must establish that physical and functional interfaces between modules conform to the approved design and that shared systems have sufficient capacity, redundancy, isolation capability, and reliability under both normal and accident conditions. In addition, inspection should consider common-cause failures, dependencies among modules, maintenance configurations, simultaneous operating states, and potential propagation of failures between modules.

Digital interoperability represents an additional dimension of this issue. Where multiple modules share digital I&C platforms, networks, data links, or supervisory control functions, inspection must verify not only the performance of individual systems but also the integrity and independence of their interfaces. Accordingly, the inspection framework should include explicit criteria for module alignment, interface verification, shared-system performance, digital interoperability, and multi-module integrated testing.

4.3 Passive Safety-System Verification

A third major gap arises from the increased reliance of LW-SMRs on passive safety systems and inherent safety functions. Traditional inspection guidance has generally developed around active components whose performance can be demonstrated through relatively direct actuation and surveillance testing. Passive safety systems may instead depend on natural circulation, gravity, pressure differences, condensation, heat transfer, or coupled thermal-hydraulic phenomena over extended periods.

Consequently, conventional component-level inspection and short-duration functional testing may not provide sufficient evidence that the passive safety function will perform as assumed in the safety analysis. Inspection should instead establish a traceable relationship between the design assumptions, physical configuration, experimental or test basis, analytical models, scaling relationships, instrumentation, uncertainty treatment, and actual plant performance.

Particular attention should therefore be given to functional demonstration, test representativeness, scaling validation, analytical-code applicability, instrumentation adequacy, material condition, uncertainty management, and long-term reliability monitoring. This represents a shift from inspection based primarily on component operability toward inspection based on demonstrated safety function and the continued validity of the underlying safety case.

4.4 Digital I&C and Cybersecurity

The increasing use of digital instrumentation and control (I&C) systems represents another important area of regulatory inspection development. Existing inspection practices are generally more mature for physical equipment than for software-dependent safety functions. LW-SMRs may employ highly integrated digital platforms, field-programmable gate array (FPGA) based automated control functions (FPGA), advanced human–machine interfaces, and networked systems, thereby increasing the importance of software verification and validation, configuration management, cybersecurity, independence, segregation, and common-cause failure assessment.

Inspection should therefore encompass the complete digital lifecycle, including software development and verification processes, configuration control, system integration testing, cybersecurity controls, communication interfaces, human–machine interfaces, and the consistency between digital system behavior and the assumptions used in the safety analysis. These requirements should be integrated with, rather than separated from, conventional I&C inspection activities.

4.5 FOAK Validation and Supply-Chain Oversight

Additional gaps arise from the first-of-a-kind (FOAK) nature of many SMR designs and their associated manufacturing and supply chainabilitys. Unlike mature large-reactor technologies with extensive operating experience, FOAK SMRs may involve innovative components, manufacturing processes, materials, passive safety functions, and integrated system configurations for which proven operating experience is limited.

The inspection framework should therefore provide enhanced regulatory hold points during prototype testing, manufacturing qualification, commissioning, and early operation. Where multiple suppliers contribute to the final plant, inspection should also verify the adequacy of supply-chain quality assurance, supplier qualification, manufacturing consistency, configuration management, and transfer of safety-significant information between organizations. FOAK inspection should consequently be closely linked to design validation and operating-experience feedback so that evidence generated during early deployment can be incorporated into subsequent modules and future plants.

4.6 Regulatory Treatment of Non-Safety SSCs

The gap analysis also identifies the need to strengthen regulatory treatment of non-safety SSCs that nevertheless have significant implications for plant safety. Conventional safety classification alone may not adequately identify the contribution of certain non-safety systems to accident prevention, mitigation, reliability, or defense-in-depth (DiD).

Accordingly, the LW-SMR inspection framework should incorporate risk-informed categorization and Regulatory Treatment of Non-Safety Systems (RTNSS) principles where appropriate. The objective is not to classify all such SSCs as safety-related, but to establish an appropriate level of inspection, quality assurance, surveillance, and reliability monitoring commensurate with their safety significance. This approach would allow regulatory resources to be focused on SSCs that materially contribute to risk reduction while avoiding unnecessary application of the highest regulatory requirements to low-significance equipment.

4.7 Decommissioning and Emergency Preparedness

The life-cycle gap analysis further identifies areas requiring additional consideration in module-based decommissioning and emergency preparedness. The physical and operational characteristics of multi-module SMRs may permit staged construction, operation, shutdown, and decommissioning of individual modules. Consequently, decommissioning inspection should address module-specific configuration, isolation, dismantling, radioactive material management, and interfaces with operating modules.

Emergency preparedness also requires consideration of SMR-specific characteristics, including reduced emergency planning zones (EPZs), module-specific accident conditions, potential aggregate source terms, simultaneous events affecting multiple modules, and shared emergency response resources. Inspection should therefore verify that emergency planning assumptions remain consistent with the approved design basis and that emergency arrangements remain effective under relevant multi-module operating states.

4.8 Overall Gap Assessment

Taken together, these findings demonstrate that the regulatory inspection gaps are distributed across the entire LW-SMR life cycle rather than being concentrated at a single licensing stage. The most significant deficiencies occur at the interfaces between manufacturing and site construction, individual modules and shared systems, passive safety functions and their analytical bases, digital systems and plant safety functions, and design assumptions and operational evidence.

Quantitatively, the study identified 107 inspection items across 13 technical areas that require either substantial supplementation of existing guidance or the development of new SMR-specific inspection criteria. This finding does not indicate that the existing Korean inspection framework is fundamentally inadequate. Rather, it demonstrates that, when applied to LW-SMRs, existing requirements often need additional inspection criteria, verification methods, and regulatory mechanisms to address safety-significant activities and evidence that are less prominent in conventional large reactor inspection.

The magnitude of this finding suggests that incremental modifications to existing inspection guidance alone are unlikely to provide a sufficiently coherent SMR inspection framework. Instead, a more systematic approach is required in which existing inspection requirements are retained where directly applicable but supplemented by SMR-specific manufacturing oversight, life-cycle inspection hold points, integrated multi-module verification, passive-system performance assurance, digital I&C inspection, risk-informed treatment of non-safety SSCs, FOAK validation, and module-specific emergency and decommissioning provisions.

Representative gaps are summarized in Table 3. The most significant gaps arise from the distinctive deployment and technological characteristics of LW-SMRs, particularly factory-based fabrication, multi-module configurations, passive safety systems, highly digitalized I&C architectures, risk-significant non-safety SSCs, and SMR-specific emergency preparedness. For example, factory fabrication may shift safety-significant activities such as welding, nondestructive examination, material verification, pressure testing, and factory acceptance testing outside the conventional site-based inspection regime. Similarly, module interfaces and shared systems

require inspection beyond module-by-module verification, including common-cause failures, dependencies, and integrated system performance. Passive safety systems also require inspection approaches that establish traceability among design assumptions, test evidence, analytical models, scaling effects, and actual plant performance.

The major gaps are associated with factory-based module fabrication, multi-module configurations and shared systems, passive safety systems, digital I&C and cybersecurity, risk-significant non-safety SSCs, and integrated commissioning. These gaps primarily result from the shift of safety-significant activities from the nuclear site to manufacturing facilities and from the increased importance of module interfaces, passive functions, and integrated system performance. Accordingly, the existing inspection framework should be supplemented with SMR-specific inspection activities, including factory inspection and hold points, configuration and traceability verification, interface and shared-system testing, passive-system performance validation, and risk-informed inspection of safety-significant functions. The representative items in Table 3 therefore illustrate how conventional inspection requirements can be adapted or extended rather than replaced for LW-SMR deployment.

5. Key Findings by Inspection Domain

The gap analysis identified 107 inspection items across 13 technical areas, of which 98 items require either supplementation of existing requirements or the development of new SMR-specific inspection criteria. This finding does not indicate a fundamental inadequacy of existing regulatory inspection framework. Rather, existing large-reactor inspection requirements remain an important foundation for pressure-boundary inspection, welding and material verification, quality assurance, and conventional functional testing, but their detailed application must be reconfigured to reflect the distinctive delivery and safety characteristics of LW-SMRs.

Five priority inspection domains were identified. First, factory fabrication, transportation, and supply-chain oversight require regulatory visibility before modules reach the nuclear site, including manufacturing verification, factory acceptance testing, shipment readiness, post-transport condition verification, and clearly defined inspection hold points. Second, passive safety systems and FOAK technologies require staged verification of design assumptions, scaling and test methodologies, analytical models, uncertainty, integrated commissioning, and operational reliability. Third, multi-module and shared-system configurations require inspection of module interfaces, shared-system capacity and isolation, common-cause failures, system dependencies, and integrated multi-module performance. Fourth, digital I&C, software, cybersecurity, and human factors require enhanced verification and validation, configuration management, cybersecurity assessment, and integrated control-room verification. Fifth, risk-significant non-safety SSCs, emergency preparedness, and decommissioning require graded regulatory treatment that reflects the safety significance of non-safety systems, aggregate source terms, multi-module operating conditions, and module-based decommissioning.

5.1 Factory Fabrication, Transport, and Site Interfaces

The most immediate regulatory gap arises because major module activities may be completed before site installation. If an inspection opportunity is missed before closure of an integral vessel or module, later site inspection cannot reconstruct the evidence. The proposed response is a manufacturing authorization, or an equivalent legally enforceable mechanism, that requires approval of the manufacturing quality plan, inspection and test plan, hold points, nonconformance disposition process, preservation plan, and transport plan before fabrication starts. The regulatory body should retain the authority to witness selected welding, nondestructive examination, pressure testing, factory acceptance testing, and final shipping-release activities. Records should be traceable to the module identifier and preserved through installation and operation.

Transport is not a logistics afterthought. Shock, vibration, temperature, humidity, salt exposure, and preservation degradation can affect instrumentation, interfaces, and internal structures. A closed-loop transport inspection should therefore include baseline condition records, data logger configuration, route and handling controls, receiving inspection, post-transport functional checks, and discrepancy evaluation. At the site, inspection should concentrate on alignment, structural connections, welds and bolted joints, piping/cable interfaces, leakage tests, and the performance of shared SSCs.

5.2 Passive Safety, FOAK Validation, and Inspectability

Passive safety functions require a broader evidence model than conventional component operability testing. Natural circulation and passive heat transfer depend on geometry, elevations, flow resistance, heat-transfer surfaces, inventories, instrumentation, and boundary conditions. The inspection objective is not to demand full-scale testing for every phenomenon; it is to verify that the applicant has established a traceable validation hierarchy that links separate-effect tests, integral tests where practicable, code validation, scaling analysis, uncertainty quantification, and plant-specific confirmation tests. The hierarchy should be subject to configuration control so that design changes trigger re-evaluation of the applicable evidence [8,9].

FOAK equipment magnifies this issue because operational feedback is limited. A staged regulatory confirmation process is proposed: design verification;

prototype or representative demonstration; manufacturing verification; pre-operational system confirmation; fuel loading and initial criticality hold points; low-power tests; staged power ascension; and early-operation reliability review. At each stage, acceptance should be linked to predefined success criteria and to an explicit process for resolving deviations. This approach supports learning without allowing accumulated uncertainty to be deferred to commercial operation.

Compact integral configurations also necessitate an inspectability case. Where conventional ASME Section XI examination access is impracticable, the applicant should justify alternative methods before construction. Possible evidence can include qualified remote visual examination, acoustic emission, guided-wave ultrasonics, leakage monitoring, vibration diagnostics, online condition monitoring, and fracture-mechanics or degradation-management analyses. The alternative should be evaluated against the degradation mechanism and the required detection capability, not selected solely for convenience.

5.3 Multi-Module, Digital I&C, and Emergency Preparedness

A multi-module plant cannot be evaluated by repeating a single-module inspection. Shared electrical systems, heat sinks, cooling systems, control rooms, maintenance resources, and emergency arrangements create dependency paths. Inspection must therefore verify the independence assumptions in the safety analysis, resource capacity under concurrent module conditions, isolation and restoration approach, common-cause failure defenses, and human performance during simultaneous alarms or abnormal evolutions. Integrated commissioning should include credible combinations of module operating states and shared-system outages.

For digital I&C, the inspection basis should cover requirements traceability, software development lifecycle controls, independent verification and validation, configuration and change control, cybersecurity integration, digital common-cause failure defenses, and human-factors engineering. The scope should include both centralized multi-module control-room functions and module-specific protections. Digital manufacturing records and testing artifacts should be auditable across supplier tiers [13–15].

Emergency preparedness should be performance- and risk-informed, while maintaining conservative protection during FOAK deployment. Any proposal for an emergency planning zone (EPZ) tailored to SMR characteristics must demonstrate, through source-term and consequence analysis, that protective-action objectives are met. The assessment must consider aggregate source terms for credible multi-module events, common-cause hazards, and the feasibility of protective actions in the actual host-community context. A reduced planning zone cannot be justified solely by unit power or by a single-module analysis [11, 15].

6. Proposed Graded Regulatory Inspection Framework

Based on the inspection gaps identified in the preceding analysis, this study proposes a regulatory inspection framework consisting of five mutually reinforcing elements. The framework is intended to preserve the fundamental structure of existing nuclear regulatory system while introducing graded, risk-informed, and life-cycle-based mechanisms that address the distinctive characteristics of LW-SMRs.

6.1 Manufacturing Approval and Factory Inspection

The first element is the establishment of a manufacturing approval and regulatory supervision mechanism prior to site construction authorization. Because safety-significant modules and components may be fabricated, assembled, tested, and prepared for transportation before they are delivered to the nuclear site, regulatory involvement should begin at the manufacturing stage.

The proposed mechanism would provide the regulatory authority with an explicit basis for establishing manufacturing inspection conditions, identifying mandatory inspection hold points, witnessing factory acceptance tests, and reviewing preservation and shipment controls. Particular attention should be given to safety-significant welding, nondestructive examination, material traceability, configuration control, dimensional verification, pressure testing, and factory acceptance testing. This approach would ensure that safety-significant evidence generated during manufacturing remains traceable and independently verifiable throughout subsequent stages of the plant life cycle.

6.2 ITAAC-Like Phased Pre-Operational Verification

The second element is the introduction of an ITAAC-like mechanism for phased pre-operational inspection and verification. Conventional inspection practice tends to concentrate on commissioning and final confirmation after construction has substantially progressed. For LW-SMRs, however, safety evidence is generated progressively from manufacturing through installation, testing, and commissioning. A single end-stage verification is therefore insufficient to capture the full chain of safety evidence.

The proposed approach would establish predefined inspection, test, analysis, and acceptance criteria at major stages of the project. These stages could include completion of module fabrication, site installation and interface verification, readiness for fuel loading, initial criticality, low-power testing, and power ascension. Regulatory hold points would be established where appropriate so that progression to the next stage is contingent upon satisfactory completion and verification of the relevant acceptance criteria.

This phased approach would be particularly valuable for FOAK designs and multi-module plants, where design assumptions, manufacturing processes, module interfaces, and integrated system performance may require progressive confirmation. It would also provide a structured mechanism for maintaining configuration consistency between the approved design, manufactured modules, installed plant, and operational configuration.

6.3 Risk-Informed Safety Classification

The third element is the introduction of a risk-informed safety classification (RISC) to supplement the existing deterministic safety classification system. Deterministic classification remains necessary because it establishes fundamental safety functions and regulatory requirements. However, deterministic classification alone may not adequately distinguish SSCs according to their actual contribution to plant risk, particularly where non-safety SSCs perform functions important to defense in depth or accident prevention.

The proposed RISC framework categorizes SSCs according to both their safety classification and their probabilistic importance. An illustrative four-category structure is proposed:

A1: Safety-related and risk-important SSCs

A2: Safety-related but not risk-important SSCs

B1: Non-safety-related but risk-important SSCs

B2: Non-safety-related and not risk-important SSCs

The categorization should consider deterministic safety functions together with probabilistic measures such as Risk Achievement Worth (RAW), Fussell–Vesely importance, and changes in core damage frequency (ΔCDF), as applicable. These assessments should be performed using a quality-assured probabilistic safety assessment (PSA) that appropriately considers relevant internal and external hazards, operating modes, and plant configurations.

Importantly, the numerical thresholds used to distinguish the RISC categories should be established through an appropriate regulatory process. The illustrative values used in the study should therefore be regarded as analytical examples rather than regulatory thresholds to be adopted directly.

6.4 RTNSS and Reliability Assurance Program

The fourth element is the establishment of Regulatory Treatment of Non-Safety Systems (RTNSS) together with a Reliability Assurance Program (RAP) for non-safety SSCs that are nevertheless important to nuclear safety.

This provision is particularly important for passive LW-SMRs because certain non-safety SSCs may contribute to defense in depth, prevent challenges to safety systems, support accident mitigation, maintain important plant functions, or avoid adverse interactions between safety-related systems. If such SSCs are regulated solely according to their deterministic classification, risk-significant B1 SSCs could fall into a regulatory gap.

Accordingly, B1 SSCs should receive a level of regulatory treatment proportionate to their demonstrated risk significance. RTNSS requirements should establish the applicable safety function, design and performance attributes, testing and surveillance requirements, maintenance basis, environmental and seismic considerations, where applicable, and performance-monitoring indicators.

The Reliability Assurance Program (RAP) should provide a systematic mechanism for maintaining and demonstrating the reliability of safety-significant SSCs throughout the entire plant life cycle. Reliability targets established during the design stage should be systematically linked to manufacturing qualification, commissioning tests, surveillance programs, maintenance activities, and operational performance monitoring. During plant operation, the RAP should periodically review the inventory of risk-significant SSCs, assess failure and availability data, monitor corrective actions, incorporate relevant operating experience, and determine whether the scope or frequency of regulatory inspection should be adjusted.

In this way, the RAP establishes a continuous feedback process in which design assumptions are verified through manufacturing and commissioning evidence, validated through operational performance, evaluated through reliability assessment, and used to inform subsequent inspection requirements. This feedback mechanism enables the inspection program to remain responsive to actual plant performance and ensures that the regulatory approach evolves as additional reliability and operating experience becomes available.

6.5 Module-Based Decommissioning and Risk-Informed Emergency Preparedness

The fifth element extends the proposed inspection framework to the downstream stages of the plant life cycle. The modular architecture of LW-SMRs may allow individual modules to be shut down, isolated, or decommissioned while other modules remain operational. Accordingly, the regulatory framework should provide a module-based decommissioning approval and inspection process that addresses module-specific configuration, radioactive material management, dismantling activities, interfaces with operating modules, and final status verification.

Emergency preparedness should likewise be adapted to the characteristics of multi-module SMR facilities. Where reduced emergency planning zones or alternative emergency response arrangements are proposed, the regulatory basis should explicitly consider the approved source-term analysis, aggregate source terms from multiple modules, simultaneous or interacting events, shared emergency resources, and the characteristics of the surrounding population and industrial environment.

6.6 Integrated Graded Inspection Approach

The five proposed regulatory elements should be implemented as an integrated system rather than as separate measures. The proposed framework establishes a continuous inspection process throughout the LW-SMR life cycle. Regulatory inspection activity begins with manufacturing, where initial safety evidence is generated and verified, and continues through module installation, interface verification, integrated commissioning, operation, reliability monitoring, and eventual module-based decommissioning.

Phased ITAAC-like verification refers to a staged verification process, similar to the U.S. ITAAC framework, in which prescribed inspections, tests, analyses, and acceptance criteria are progressively confirmed to demonstrate that manufactured, installed, and commissioned SSCs conform to the approved design and applicable regulatory requirements. The phased ITAAC-like verification and acceptance process provides a structured means of confirming that the manufactured and installed plant conforms to approved design requirements, while RISC provides the basis for differentiating inspection requirements according to the safety and risk significance of SSCs. RTNSS and the Reliability Assurance Program further ensure that non-safety SSCs with significant risk contributions remain subject to appropriate regulatory inspection during operation.

Under this approach, inspection intensity is determined by both deterministic safety functions and probabilistic risk significance. A1 SSCs would receive the highest level of regulatory attention, whereas A2, B1, and B2 SSCs would be subject to progressively graded inspection requirements. This graded approach is intended not to reduce regulatory inspection activities, but to focus regulatory resources on SSCs and functions that are most important to nuclear safety.

Overall, the proposed framework represents a transition from a predominantly uniform and site-centered inspection model to a graded, life-cycle-based, risk-informed, and performance-oriented system. At the same time, it preserves the fundamental structure of existing regulatory framework while providing explicit inspection mechanisms to address the manufacturing, modularization, passive safety, digitalization, multi-module operation, and other distinctive characteristics of LW-SMRs.

Table 4 presents an illustrative RISC-based graded inspection approach for differentiating regulatory inspection requirements according to the deterministic safety classification and probabilistic risk significance of SSCs. The table categorizes SSCs into four groups such as A1, A2, B1, and B2 and illustrates how inspection scope, verification requirements, testing, quality assurance, and regulatory inspection activities can be proportionately applied to each category. The proposed classification is intended as a conceptual framework rather than a fixed regulatory standard, and the specific classification criteria such as Risk Achievement Worth (RAW) and Fussell-Vesely Importance (FV), and numerical thresholds should be established through a formal regulatory process.

7. Proposed Life-Cycle Inspection Framework

Table 5 presents the proposed life-cycle-based regulatory inspection framework for LW-SMRs. The framework maintains the existing construction and operating licensing decision points while introducing additional evidence gates that correspond to the major stages of the SMR life cycle. This staged approach is intended to ensure that safety-significant evidence is generated and verified at the point where it is most accessible and meaningful. In particular, inspections that may become irreversible or difficult to reproduce after module closure or shipment are performed during manufacturing, while module interfaces and shared systems are verified during site assembly and commissioning. Operational performance data are subsequently incorporated into reliability assessment and used to inform the scope and frequency of future regulatory inspection program.

Implementation of the proposed framework should initially be undertaken through a pilot application to the first i-SMR design, rather than through immediate and comprehensive codification of all SMR-specific inspection requirements. The initial regulatory products should include a manufacturing and transportation inspection guide; a passive-safety and FOAK evidence-verification guide; a multi-module and shared-SSC inspection guide; a graded inspection and PSA quality-assurance guide; and a digital I&C and quality-assurance inspection guide. The experience and findings obtained from the pilot application should then be systematically evaluated and incorporated into a controlled revision process before the framework is applied to subsequent SMR projects.

This phased implementation strategy would allow the regulatory authority to identify practical issues, validate inspection criteria, and refine regulatory hold points while maintaining consistency with the existing licensing framework. It would also reduce regulatory uncertainty associated with first-of-a-kind deployment and provide a structured mechanism for incorporating operating experience and inspection feedback into subsequent regulatory requirements.

Table 6 presents the proposed institutional reform package for LW-SMR regulatory inspection, focusing on the organizational, legal, procedural, and technical measures required to support implementation of the proposed life-cycle inspection framework. The package is intended to complement existing regulatory arrangements rather than replace them. It includes measures for establishing manufacturing-stage regulatory authority, strengthening supplier and factory inspection capabilities, introducing SMR-specific inspection guidance and hold points,

developing risk-informed and graded inspection criteria, and enhancing regulatory expertise in passive safety, multi-module systems, digital I&C, cybersecurity, FOAK technologies, and reliability assurance. It also addresses the need for inter-organizational coordination, inspector training, operating-experience feedback, and periodic revision of inspection guidance. Collectively, these measures provide the institutional foundation necessary to transition from a predominantly site-centered inspection system to a life-cycle-based, risk-informed, and performance-oriented regulatory inspection framework for LW-SMRs.

8. Discussion and Conclusion

The deployment of LW-SMRs requires a regulatory inspection framework that is as modular, risk-informed, and life-cycle-oriented as the technology itself. The proposed framework is not intended to reduce regulatory scrutiny, but rather to redirect regulatory attention toward the safety-significant evidence generated by SMR manufacturing, modular construction, passive safety functions, digital systems, and multi-module operation. Accordingly, inspection resources should be concentrated on SSCs and functions with greater safety significance while avoiding disproportionate oversight of items with demonstrably low safety significance. Such a graded approach requires a high-quality PSA, a clear deterministic safety basis, and explicit treatment of uncertainty.

The analysis of 107 inspection items shows that existing large-reactor-oriented inspection guidance provides a valuable foundation but requires substantial supplementation for LW-SMR applications. The principal gaps are associated with factory fabrication and transportation, passive safety and FOAK validation, multi-module and shared systems, risk-significant non-safety related SSCs and reliability management, digital I&C, emergency preparedness, and module-level decommissioning. These gaps arise primarily because SMRs shift important safety evidence from the nuclear site to manufacturing facilities and supply chains and introduce new interfaces among modules, shared systems, passive functions, and digital architectures.

A practical regulatory response is to retain the existing licensing framework while introducing five complementary measures: (1) manufacturing authorization and associated factory and transportation inspection hold points; (2) site interface and shared-system verification; (3) ITAAC-like integrated pre-operational verification; (4) RISC, RTNSS, and RAP-based graded operational oversight; and (5) module-level emergency preparedness and decommissioning verification. Together, these measures would establish continuous regulatory inspection from manufacturing through operation and decommissioning.

The proposed approach also enables regulatory resources to be allocated according to safety significance, design maturity, and the importance of irreversible or difficult-to-repeat evidence. It provides enhanced oversight where safety evidence must be captured before module closure or shipment, while allowing appropriately graded inspection for lower-significance SSCs. At the same time, FOAK deployment can be used as an opportunity to collect operating experience and reliability data, which can subsequently inform inspection scope, frequency, and requirements for repeat SMR deployment.

This study is a regulatory gap analysis rather than a plant-specific safety case. Therefore, the proposed priorities and RISC approach should be further validated against an i-SMR design. Future work should refine RISC and PSA criteria, develop detailed inspection acceptance criteria, establish measurable RAP performance indicators, and evaluate the practical inspection burden and safety benefits at key manufacturing and commissioning hold points.

Overall, the proposed framework provides a practical pathway from a predominantly site-centered and large-reactor-oriented inspection model toward a graded, life-cycle-based, risk-informed, and performance-oriented system.

By maintaining the existing regulatory foundation while incorporating SMR-specific inspection mechanisms, the proposed framework can strengthen regulatory assurance and establish a predictable, technically responsive basis for the future licensing, construction, and deployment of i-SMR.

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Table 1. LW-SMR design features and inspection implications

Attribute	Conventional large LWR	LW-SMR	Inspection implication
Fabrication location	Predominantly on-site	Factory-based modular fabrication	Need manufacturing-stage regulatory visibility and factory acceptance oversight
Inspection sequence	After installation in staged construction	During fabrication plus site assembly	Need additional inspection triggers before shipment and sealing
Safety-system architecture	Active systems dominant	Passive systems emphasized	Need functional demonstration, uncertainty evaluation, and reliability-based surveillance
Plant configuration	Single-unit focus	Multi-module with shared systems	Need interface, common-cause, and aggregate-risk inspections
Reactivity control	Conventional soluble-boron-based PWR practice	Reduced-boron or boron-free options possible	Need new verification for alternate reactivity-control methods
Control architecture	Mixed analog/digital legacy base	Highly digitalized integrated control	Need software V&V, cybersecurity, and HFE inspection

Table 2. Summary of Representative Inspection Gaps and Regulatory Priorities for LW-SMRs

Technical area		Items	Primary lifecycle stages	Priority rationale
1	Modular construction and factory fabrication	7	Factory; site assembly	Factory-based fabrication requires enhanced regulatory visibility, factory inspection, hold points, and manufacturing traceability before module delivery.

2	Multi-module operation and shared SSCs	7	Design; pre-operational; operation	Multi-module configurations require enhanced verification of module interfaces, shared-system capacity and isolation, dependencies, and common-cause effects.
3	Passive safety systems	6	Design; pre-operational; operation	Passive safety functions require additional verification of functional performance, scaling, analytical models, and long-term reliability.
4	RTNSS	5	Design; pre-operational; operation	Conventional safety classification may not adequately capture the risk significance of non-safety SSCs.
5	Digital I&C and cyber security	6	Design; factory; pre-operational; operation	Highly digitalized I&C systems require enhanced verification of software V&V, cybersecurity, interfaces, and configuration management
6	Helical steam generators	15	Design through operation	Technology-specific fabrication and in-service inspection methods require enhanced verification of tube integrity, manufacturing quality, and NDE.
7	Steel Integral reactor vessel	8	Factory through operation	For LW-SMR integral reactor vessels, inspection should cover the entire life cycle, from manufacturing and pre-service inspection to risk-informed ISI during operation. Particular attention should be given to weld integrity, NDE, material quality, difficult-to-access areas, and continuous vessel integrity monitoring.
8	Integral reactor	8	Factory through operation	The pressure-boundary features that are not fully addressed by conventional large-reactor inspection practices.
9	Steel-plate concrete containment	10	Design through operation	Composite steel-plate and concrete construction requires enhanced verification of liner integrity, connections, embedded components, concrete quality, and structural performance.
10	FOAK design elements	7	Design; factory; pre-operational	Limited operating experience requires enhanced verification of design assumptions, qualification, testing, and manufacturing evidence
11	Emergency preparedness	10	Design; pre-operational; operation	Reduced EPZ and aggregate source-term issues are underdeveloped
12	Decommissioning and Radioactive waste management	8	Operation; decommissioning	Module-specific isolation, dismantling, and radioactive material management require additional decommissioning inspection criteria.
13	Supply chain	10	Design through operation	Globalized supply chains require enhanced verification of supplier qualification, quality assurance, manufacturing controls, and component traceability.

Table 3. Representative SMR-Specific Inspection Items and Regulatory Gaps

No.	Inspection Item	Existing Guidance Applicability	Identified Gap	SMR-Specific Inspection Requirement
1	Factory fabrication of safety-significant modules	Supplementation	Manufacturing activities may be completed before site delivery	Verify welding, NDE, material control, dimensional control, pressure testing, and factory acceptance at the manufacturing facility
2	Manufacturing inspection	New / Supplementation	Conventional inspections are mainly site-based	Establish regulatory hold points before completion or shipment of safety-significant modules

3	Module configuration and traceability	Supplementation	Configuration changes during fabrication and transport may be difficult to verify	Verify configuration records, identification, traceability, and as-built conformity from factory to site
4	Module-to-module interfaces	New / Supplementation	Conventional inspection is primarily unit-based	Verify mechanical, electrical, I&C, and functional interfaces between reactor modules
5	Shared systems supporting multiple modules	New / Supplementation	Capacity, redundancy, isolation, and dependency among modules require additional verification	Verify shared-system capacity, independence, isolation, reliability, and performance under multi-module conditions
6	Passive safety-system performance	Supplementation	Conventional surveillance testing may not adequately demonstrate passive functions	Verify natural circulation, gravity-driven functions, heat transfer, test evidence, scaling, and analytical validation
7	Long-term passive-system reliability	New / Supplementation	Short-duration functional tests may not demonstrate long-term performance	Verify degradation monitoring, instrumentation, uncertainty treatment, and long-term reliability evidence
8	Digital I&C interfaces and interoperability	Supplementation	Multiple modules may share digital platforms and communication networks	Verify data interfaces, communication integrity, functional independence, configuration control, and interoperability
9	Cybersecurity of shared digital systems	Supplementation	Shared digital architecture creates additional interconnection and dependency risks	Verify cybersecurity controls, network segregation, access control, and configuration management
10	Risk-significant non-safety SSCs	Supplementation / New	Conventional safety classification may not capture risk-significant non-safety functions	Verify SSC categorization and inspection commensurate with safety and risk significance
11	FOAK design and technology validation	New / Supplementation	Limited operating experience and first-of-a-kind design features	Verify design assumptions, qualification evidence, testing, and resolution of technology-specific uncertainties
12	SMR emergency preparedness	Supplementation / New	Conventional emergency-planning assumptions may not fully reflect SMR characteristics	Verify source-term assumptions, multi-module accident scenarios, emergency response arrangements, and applicable planning criteria
13	Integrated commissioning and acceptance testing	Supplementation / New	Individual component tests may not demonstrate integrated SMR performance	Verify integrated plant functions, module interactions, shared systems, and conformity with the approved safety basis
14	Module-based decommissioning	Supplementation	Conventional inspection frameworks are not specifically structured for modular dismantling	Verify module isolation, dismantling sequence, radioactive material control, and configuration management

Note: These representative items are derived from the gap-analysis framework, which classified inspection requirements as directly applicable, applicable with supplementation, or requiring new criteria. The overall analysis identified 107 inspection item

Table 4. Illustrative RISC-based graded inspection approach

Class	Definition	Illustrative criteria	Indicative inspection treatment
A1	Safety-related and risk-significant	RAW ≥ 2.0; FV ≥ 0.1	Full QA controls, full witness coverage, annual testing
A2	Safety-related but lower risk significance	RAW < 2.0; FV < 0.1	Graded QA, selective witness points, biennial testing

B1	Non-safety but risk-significant	RAW ≥ 2.0 and/or high operational importance	RTNSS + RAP, augmented QA, periodic functional verification
B2	Non-safety and low risk significance	Low RAW/FV	Document review, commercial-grade controls, extended surveillance interval

Table 5. Proposed life-cycle regulatory inspection framework for LW-SMRs.

Stage	Primary regulatory objective	Representative inspection outputs
1. Design readiness and manufacturing authorization	Confirm design maturity, manufacturing controls, and inspection hold points before irreversible fabrication.	Approved manufacturing QA/ITP; supplier qualification; FOAK validation plan; digital configuration baseline; transport plan.
2. Factory fabrication and transport	Verify that module attributes and records conform to approved commitments.	Witnessed hold points; NDE and pressure-test records; FAT evidence; nonconformance closure; shipping release; transport condition data.
3. Site assembly and shared-system installation	Confirm interfaces, alignment, connection integrity, and shared-system configuration.	Receiving inspection; alignment/connection tests; leak and functional tests; shared-SSC capacity and isolation confirmation.
4. Pre-operational and commissioning verification	Demonstrate integrated performance against predefined acceptance criteria.	ITAAC-like completion evidence; passive-system confirmation; digital I&C validation; multi-module integrated tests; fuel-load/criticality/power hold points.
5. Operation and periodic oversight	Maintain safety functions through graded inspection and performance monitoring.	RISC/RTNSS inspection plan; RAP indicators; alternative ISI results; digital change reviews; operating-experience feedback.
6. Module-level decommissioning verification	Control selective module retirement, removal, waste, and site interfaces.	Module isolation/removal plan; radioapproachal characterization; remote-work validation; waste classification and transport records.

Table 6. Proposed Institutional Reform Package for LW-SMR Regulatory Inspection

Reform element	Purpose	Expected regulatory benefit
Manufacturing approval	Create legal basis for module fabrication, FAT, and transport oversight before construction	Closes inspection blind spot at factory stage
ITAAC-like progress verification	Tie design commitments to staged inspection and test acceptance criteria	Improves traceability during FOAK deployment and multi-module commissioning
RISC adoption	Supplement deterministic safety classes with quantified risk significance	Allocates inspection intensity more rationally
RTNSS + RAP	Control non-safety yet risk-significant systems across the life cycle	Preserves safety without overextending full safety-grade requirements
Module-based decommissioning and risk-informed EPZ	Adapt end-of-life and emergency planning to modular plants and aggregate source terms	Improves legal fit for multi-module SMRs

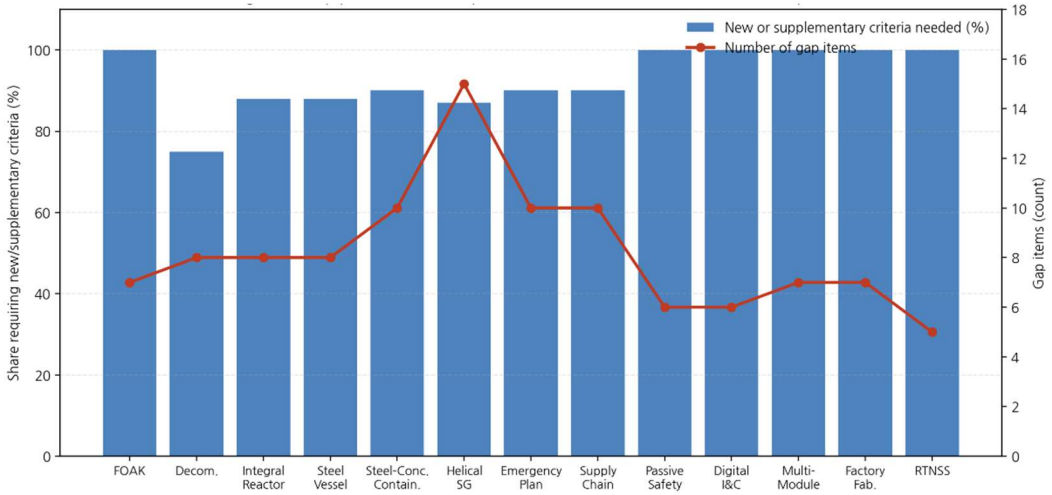


Figure 1. Gap Profile of LW-SMR Inspection Domains