Safeguards-by-Design for the Development of Next-Generation Reactors: Policy and Technical Perspective

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1. Introduction

The global movement toward carbon neutrality requires a paradigm shift in nuclear energy technologies. Among the alternatives to conventional large reactors, small modular reactors (SMRs) are attracting increasing attention because of their inherent advantages, such as shorter construction times, lower initial investment costs, and improved site utilization efficiency [1]. Nations around the world are engaged in competitive development of SMR technologies, and South Korea has also begun development of a pressurized water reactor (PWR) type SMR, with standard design approval application expected around 2026 [1].

The innovative small modular reactor, called i-SMR, offers advantages over conventional PWRs in terms of reduced physical size and design complexity, simplified coolant systems, and the implementation of passive safety systems that provide a high level of safety even in the absence of external power or operator intervention. In particular, the concepts of soluble boron-free (SBF) operation and multi-module deployment have emerged as the most distinctive and transformative design features [2].

However, these innovations pose new challenges with respect to nuclear safeguards as regulated by the International Atomic Energy Agency (IAEA). The current IAEA safeguards system is standardized around conventional large reactors, and its applicability to SMRs may be limited due to differences in design philosophy, operational structure, and physical layout [2].

Safeguards-by-Design (SBD) is a proactive framework that integrates regulatory requirements namely material control and accountancy (MC&A), containment and surveillance (C/S) into reactor design from the earliest stages of development [2]. This approach has been advanced by the U.S. Department of Energy (DOE) in cooperation with the IAEA under the Next Generation Safeguards Initiative (NGSI) [3]. It is also seen as a strategic enabler for building international confidence in nuclear export capabilities.
In particular, non-standard reactors such as SMRs pose significant challenges for safeguards implementation. Due to their compact design, modular structure and lack of conventional control systems (e.g. soluble boron-free), SMRs inherently complicate the use of standard safeguards equipment. In particular, the absence of a chemical and volume control system (CVCS) results in more complex neutron economy management and potentially more heterogeneous fuel burnup profiles, making conventional inspection and measurement tools less effective. These concerns are consistent with the IAEA's growing emphasis on "effective and non-invasive safeguards measures” [2].

The purpose of this study is to examine how design features of i-SMR - in particular, soluble boron-free operation and multi-module deployment - affect IAEA safeguards systems, and to propose structural strategies for implementing Safeguards-by-Design (SBD) that address these challenges.

2. Design Features of i-SMR and SBD

i-SMR are characterized by a combination of features including low power, modular design, and implementation of passive safety systems, all of which contribute to simplified operation and improved safety [1, 2]. Two of the most notable design innovations are SBF operation and multi-module deployment.
In conventional PWRs, soluble boron is added to the coolant to absorb neutrons and regulate core reactivity. In contrast, SBF operation eliminates this soluble chemical control mechanism and instead relies on fixed reactivity control methods such as control rods, burnable absorbers, and optimized fuel assembly layouts [2, 3].
Importantly, in the case of i-SMR, this boron-free approach extends even to accident scenarios. The i-SMR design does not include a boron injection system under either normal or emergency conditions. Instead, reactivity shutdown and decay heat removal are provided by passive safety systems, allowing the reactor to remain safe without operator intervention or external power during emergencies [3].
Multi-module deployment refers to the configuration in which multiple i-SMR units, built off-site and delivered as modules, are installed and operated in parallel at a single site. This design allows for high flexibility as additional capacity can be added as needed and modules can be maintained independently [1, 2].

However, this operational approach poses new challenges in the context of nuclear safeguards, particularly in terms of material flow tracking, inspection burden and system integration**.**

The absence of soluble boron in i-SMR means that fine-tuned reactivity management must be achieved through core design, particularly in the arrangement of burnable absorbers and control rods. As a result, the spatial distribution of fissile material (U-235) in the reactor core may become non-uniform or non-linear, which can affect the effectiveness of NDA techniques used in safeguards [2, 4].

The compact and modular design of i-SMR inherently limits the physical space available for the installation of safeguards equipment. This poses difficulties for the integration of containment and surveillance (C/S) equipment, such as gamma cameras, neutron detectors, and seals, and requires prior planning of equipment ports, communication paths, and power access [2].

Multi-module systems often share components such as fresh fuel loading systems, spent fuel storage areas, and waste processing units. These shared elements result in multi-directional and cross-module material flows, reducing the traceability and transparency required by IAEA safeguards and necessitating centralized safeguards data systems and module accounting [2, 3].

While i-SMR offer a new paradigm in reactor design through structural and system simplification, they also deviate from the structural assumptions of current IAEA safeguards systems. SBF operation poses challenges to the reliability of NDA interpretation, while the use of multiple modules complicates material flow monitoring. As a result, Safeguards-by-Design must be treated not as an option, but as a fundamental requirement to ensure verifiability and maintain non-proliferation credibility.

3. Impact of Soluble Boron-Free Operation

Soluble Boron-Free (SBF) operation refers to a design strategy in which no boron is dissolved in the reactor coolant to control core reactivity. Instead, reactivity is controlled entirely by fixed absorbers such as control rods and burnable poisons (BPs) [1, 2]. In the case of i-SMR, this SBF concept is extended beyond normal operating conditions.

The i-SMR design explicitly excludes boron injection system, and instead relies entirely on passive safety systems to perform reactivity shutdown and decay heat removal without external power or operator intervention [3].

The elimination of soluble boron represents a major shift in reactor safety philosophy. While it simplifies system architecture and reduces chemical complexity, it also introduces new variables into the nuclear safety environment, particularly with respect to material behavior under normal and abnormal conditions.

While the operational advantages of SBF are widely recognized, the approach poses non-trivial challenges to the implementation of safeguards.

SBF designs require reactivity control to be embedded in the fuel layout itself. As a result, heterogeneous distributions of U-235 and burnable poisons can occur throughout the core. These distributions deviate from the assumptions used in conventional Non-Destructive Assay (NDA), which typically assume uniform burnup and composition [2, 4]. Such deviations can lead to ambiguity in the interpretation of gamma and neutron signatures, Inaccuracies in item counts and mass balance calculations, Increased false positives or negatives during safeguards inspections.

The IAEA safeguards toolkit includes NDA equipment such as high-resolution gamma spectrometers and neutron coincidence counters calibrated for reactors with more homogeneous fissile material profiles. SBF-based i-SMR may violate these baseline assumptions, requiring either significant recalibration of existing equipment, or development of entirely new evaluation algorithms adapted to new fuel geometries [2, 4].

In response to these challenges, the following SBD strategies are recommended for i-SMR. Early provision of complete fuel layout and distribution data in the Design Information Questionnaire (DIQ), integration of advanced NDA modeling algorithms that account for non-uniform neutron and gamma flux, development of digital Safeguards Effectiveness Reports (SGERs) that include real-time updates on fuel movements and reactivity changes. These actions will assist the IAEA and KINAC in adapting its safeguards systems to i-SMR environments while maintaining the integrity and credibility of its non-proliferation efforts.

SBF operation offers significant advantages in terms of operational efficiency and safety. However, from an IAEA safeguards perspective, it introduces ambiguities in material tracking, inaccuracies in NDA measurements, and limitations in equipment compatibility. Addressing these issues requires early and thorough integration of SBD principles into the reactor design phase, as well as proactive engagement with the IAEA on scenario-based safeguards modeling. The IAEA safeguards toolkit includes NDA equipment for reactors with more homogeneous fissile material profiles. SBF-based i-SMR may violate these baseline assumptions, requiring either significant recalibration of existing equipment, or development of entirely new evaluation algorithms adapted to non-standard fuel geometries [2, 4].

4. Safeguards Strategy for Multi-Module Deployment in i-SMR

Multi-module deployment is a core architectural feature of SMRs. It refers to the operation of multiple reactor modules-constructed off-site and installed at a single plant site-in parallel or independent ways. For example, the NuScale SMR is designed to operate up to 12 modules from a central control room, while the Korean i-SMR takes a similar approach [1]. This configuration offers clear advantages in terms of scalability, operational flexibility and economic efficiency. However, it also introduces significant complexity into the safeguards implementation, particularly in terms of the multiplicity of safeguards targets, the flow of nuclear material between modules, the different operating conditions between modules [2, 3].

Nuclear Material Flow Traceability
Shared infrastructure between modules such as fuel loading systems, spent fuel storage, and waste management-creates multi-directional and overlapping material flows. This complicates the application of IAEA safeguards protocols, which are based on clear material accountancy boundaries [2].

Surveillance burden and equipment redundancy
Each module typically requires dedicated safeguards equipment such as NDA instruments, CCTV and sealing devices. As the number of modules increases, the volume and redundancy of equipment required increases accordingly, raising concerns about logistics, cost, and operational burden [3].

Asynchronous Operational States
In a multi-module deployment, each module may have a different fuel cycle, maintenance schedule, or operational phase. This asynchrony undermines the uniformity and scheduling efficiency of safeguards inspections, potentially increasing the risk of oversight [3].

Physical installation constraints
Due to the compact design of SMR modules, the installation of safeguards equipment in accordance with IAEA standards can be physically challenging. Issues such as limited access, power supply limitations and electromagnetic interference can reduce the reliability of the safeguards systems.

To address the above challenges, the following SBD based strategies are proposed for i-SMR multi-module facilities.

Hybrid Monitoring Architecture
Install only essential safeguards equipment in each module and concentrate high-precision monitoring equipment on common systems (e.g., fuel transfer channels, storage tanks). Use centralized NDA systems and neutron detectors on pathways.

Centralized Safeguards Data Server
Develop a centralized safeguards server to collect and integrate data from all modules in real time. Centrally manage and analyze NDA results, CCTV footage, and seal verification logs to quickly identify anomalies.

Integrated SGER Management
Transition from per-module to site-level Safeguards Effectiveness Reports (SGERs). Work with the IAEA to define safeguards metrics and thresholds tailored to multi-module operations.

Risk-based prioritization of module inspections
Dynamically assign safeguards inspection priorities based on module status, material movement risk, and accident potential. Strategically allocate inspection resources to high-risk areas, increasing both efficiency and coverage.

Given the asynchronous and independent nature of module operations, safeguards strategies must be tailored to each operational phase. While multi-module deployment increases the economic and operational attractiveness of i-SMR, it complicates safeguards application through increased material flow complexity, monitoring redundancy, and inspection scheduling difficulties. To address these issues, a shift to an SBD oriented integrated safeguards architecture is required. Core features should include centralized data systems, risk-based prioritization logic, and adaptive inspection schedules. These structural safeguards strategies are not only essential for maintaining compliance with IAEA standards, but also critical for building international confidence in the use and exportability of i-SMR.

5. Policy Implications and Recommendations

The use of i-SMR with SBF operation and multi-module configuration represents a significant departure from traditional reactor paradigms. While these innovations enhance economic efficiency, they also complicate the application of IAEA safeguards, requiring a strategic reevaluation of the regulatory and inspection framework [1, 2]. In particular, the complete exclusion of boron injection systems, even in accident scenarios, and the high degree of interconnectivity in multi-module sites increase the complexity of nuclear material tracking, safeguards equipment deployment, non-proliferation assurance [3]. These factors call for a policy shift towards the early integration of safeguards into design and regulation through the full adoption of the SBD framework.

Institutionalize SBD in reactor licensing Require SBD elements (e.g., surveillance ports, communication paths,

equipment mounts) to be included in design documentation (e.g., DIQ and Facility Attachments). Require pre-consultation with the IAEA on SBD compliance during the design approval process [2, 4].
Develop risk-based inspection protocols implement module-specific inspection prioritization based on operational status, accident probability, and nuclear material sensitivity. Differentiate inspection frequency and safeguards coverage accordingly.
Strengthen emergency scenario modeling develop alternative safeguards scenarios for SBF reactors without boron-based emergency shutdown capabilities.
Ensure continuity of verification under post-accident conditions through redundant data recording and digital archiving.

In addition, the R&D field for the successful SBD of i-SMR has the following directions. First, the development of an NDA measurement and analysis algorithm suitable for the non-uniform material distribution used in i-SMR fuel composition is required. [2]. Second, for effective national safeguards framework, implementation of safeguards measures by operators and regulation by regulators, it should be possible to generate and update Safeguard Effectiveness Reports (SGERs) through the development of a digital SGER system in a real-time digital platform. Fuel flow logs, maintenance schedules, and module-level events should be integrated through the established SGER. Finally, a study is needed to analyze bypass routes and access vulnerabilities through scenario-based simulation.

To ensure global acceptance and facilitate export of i-SMRs, participating in IAEA-led initiatives to standardize safeguards approaches for SMRs is recommended. Also, Korea's SBD-compliant design cases through IAEA Member State Support Programs (MSSPs) should be shared. Through these process, bilateral and multilateral pilot projects for field testing of SMR-tailored safeguards equipment and protocols would be promoted.

5. Conclusion

The innovative design features of i-SMRs represent a promising advance in nuclear energy technology. However, they also pose significant structural and operational challenges to existing safeguards systems. To address these challenges, safeguards must be integrated from the earliest design phase using the SBD methodology, supported by adaptive inspection strategies, real-time data management and risk-based surveillance protocols.

Proactively institutionalizing SBD within the domestic regulatory framework and collaborating internationally will enable Korea to not only ensure compliance with IAEA safeguards, but also to become a leader in the global SMR export market.

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