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Development on a Regulatory Frameworks of the Remote Inspection system for nuclear safeguards

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1. Introduction

Small Modular Reactors (SMRs) are widely recognized as next-generation power sources contributing to carbon neutrality. They are characterized by the deployment of multiple reactor modules within a single site and by reduced operational staffing enabled through system simplification and automation-based operation. In particular, the domestically developed Innovative Small Modular Reactor (i-SMR) consists of four reactor modules and a single spent fuel storage pool.

Such a multi-module configuration entails a distributed inventory of nuclear material and differing refueling cycles among modules. Within traditional safeguards inspection systems centered on periodic on-site inspections, these characteristics may increase the burden of verification activities and reduce inspection efficiency. While the i-SMR is used as a representative case, the proposed framework is broadly applicable to advanced reactor systems facing similar safeguards challenges.

In addition, the COVID-19 pandemic exposed the vulnerability of safeguards systems that rely heavily on physical access, underscoring the importance of maintaining Continuity of Knowledge (CoK) regarding the location, status, and integrity of nuclear material even under restricted-access conditions.

The i-SMR features a multi-module configuration with a shared spent fuel storage pool, resulting in distributed nuclear material inventories and module-specific refueling cycles. Such asynchronous operational characteristics may lead to monitoring gaps, as fuel replacement in one module can occur while other modules remain less actively observed. This poses limitations for maintaining CoK using conventional periodic on-site inspections alone. Furthermore, i-SMR systems are expected to operate with reduced staffing compared to large-scale nuclear power plants, potentially limiting continuous on-site verification activities. Therefore, the proposed remote inspection framework aims to complement existing inspection approaches by addressing module-level verification gaps and enabling timely detection of abnormal nuclear material movements or operational conditions.

Accordingly, this study develops a regulatory framework for institutionalizing remote inspection approaches utilizing advanced digital technologies—such as drone-based identification systems, unattended monitoring systems, and digital twin platforms—within the ROK safeguards regulatory system. The objective is to address potential verification gaps arising from multi-module configurations and reduced operational staffing in i-SMR facilities, thereby strengthening the effectiveness and resilience of safeguards implementation.

2. Institutional Developments and Technological Trends

2.1 Developments in the IAEA Safeguards Glossary

The IAEA Safeguards Glossary (2022 Edition) reflects increasing digitalization in safeguards implementation. The 2022 Edition introduces and defines the “Mailbox declaration” as the near real-time submittal, into a secure electronic mailbox, of information on operational activities of safeguards relevance. It also formalizes the concept of the Unattended Monitoring System (UMS), specifying requirements for tamper indication, data authentication, encryption, and provisions for remote data transmission.

The Glossary further clarifies that the Short Notice Random Inspection (SNRI), developed for fuel fabrication facilities under safeguards, is intended to provide 100% verification coverage of domestic transfers of nuclear material and borrowing scenarios, and is based on the near real-time submittal of mailbox declarations. This indicates that inspection unpredictability is supported not only by scheduling practices but also by electronic data submission and unattended monitoring mechanisms.

These developments demonstrate that near real-time electronic data submission and unattended monitoring are explicitly defined and referenced in safeguards terminology and inspection approaches.

2.2 Domestic and International Technological Trends

Internationally, the IAEA and its Member State Support Programmes (MSSPs) support the development and implementation of remote and autonomous verification technologies. For example, the Robotized Cerenkov Viewing Device (RCVD) has been further developed to support autonomous spent fuel verification and to enhance in-field inspection capabilities. These efforts are intended to improve the efficiency and practicability of verification activities, including reducing radiation exposure during inspections.

In ROK, research has been conducted on automated validation software designed to assess the completeness and consistency of mailbox declarations [4]. In addition, nuclear material monitoring systems utilizing digital twin and blockchain technologies have been studied as potential tools to enhance traceability and data integrity in nuclear material accountancy [5]. These studies demonstrate the technical applicability of digital tools to safeguards-relevant data handling, monitoring, and record-keeping functions in the domestic context.

However, the current Nuclear Safety and Security Commission (NSSC) Notice No. 2025-2, "Regulation on Nuclear Material Accountancy Inspections," remains structured primarily around on-site, in-person inspections and does not explicitly provide for remote inspection mechanisms. Accordingly, this study proposes institutional measures to establish a regulatory basis for recognizing remote data and digital technologies as acceptable means of safeguards verification within the national framework.

Reviewing and refining the regulatory framework in line with technological developments can facilitate the timely use of new verification technologies and strengthen their practical application in safeguards.

3. Institutionalization of Remote Inspection and Proposed Regulatory Amendments

3.1. Definition of Remote Inspection

Article 3 of the current regulation classifies nuclear material accountancy inspections into initial inspections, routine inspections, ad hoc inspections, and special inspections. This study proposes the establishment of "Remote Inspection" as an additional inspection category within this framework.

Remote inspection is defined as an inspection conducted through remote equipment and digital systems to support verification activities performed during routine inspections, or to maintain Continuity of Knowledge (CoK) during intervals between inspections in multi-module reactor facilities. It is not intended to replace routine on-site inspections but to supplement them.

The proposed framework is intended for use within the national safeguards inspection system and may complement international safeguards activities conducted by the IAEA, without implying automatic transmission of inspection data to international organizations.

Remote inspection may be applied under access-restricted conditions, in facilities with multi-module configurations, or in situations where inspection activities are expected to require substantial manpower and time, such that timely and efficient verification may not be readily achievable through on-site inspection alone.

3.2. Improvements in Inspection Frequency and Notification Procedures

Articles 5 and 6 of the current regulation, concerning inspection frequency and notification, are structured around existing inspection categories. This study proposes procedural amendments to incorporate remote inspection within the regulatory framework.

First, remote inspections are to be provided for on an ad hoc basis for the purpose of maintaining continuity of nuclear material accountancy and screening for anomalies. In a manner conceptually comparable to the SNRI approach, they are operated so as to minimize predictability while incorporating data-based screening functions.

Second, it is proposed that remote inspections be notified at least two hours prior to initiation in order to ensure procedural legitimacy and information security management. The notification should specify the target modules, review period, data scope, and required cooperation.

Table I: Comparison of Existing Inspection Types [1] and Proposed Remote Inspection

Type	Timing	Purpose	Frequency	Notification
Initial	Prior to initial receipt	Pre-receipt verification	One-time	≥10 days
Routine	Periodic	Implementation verification	≥1/year (≤14 months)	≥10 days
Ad Hoc	As needed	Implementation review	Not fixed	As provided in the regulation
Special	Specified conditions	Verification of special reports or non-compliance	Not fixed	As provided in the regulation
Remote	As needed	Maintenance of CoK	Not fixed	≥2 hours

3.3. Inspection Methodology

Remote inspection is designed as an integrated digital operational structure centered on a digital twin environment. The digital twin virtually represents the SMR facility and serves as a platform for extracting and visualizing real-time location and timestamp information of nuclear fuel assemblies. Sensor-linked data may be stored or managed using blockchain-based architectures to support data integrity and tamper resistance in nuclear material accountancy records [5].

Within this framework, independently collected measurement data from UMS and remote measurement devices are integrated and cross-validated with operator-submitted near real-time mailbox data in the digital twin environment.

The operational procedure of remote inspection can be structured as follows:

1. Collection of safeguards-relevant data through UMS and operator declarations (mailbox)
2. Integration of data within a digital twin environment and cross-validation between declared and actual operational and material movement information, including pre-verification of declared data prior to on-site inspection where necessary
3. Identification of anomalies followed by additional verification actions, including requests for further data or on-site inspections

This procedure can be utilized as a complementary verification measure between periodic inspections by supporting the maintenance of CoK regarding the location, status, and movement history of nuclear materials. Under normal conditions, CoK is preserved based on data consistency. When predefined thresholds are exceeded or discrepancies are identified between declared plans and actual material movements, automated notification functions may generate alerts to relevant parties. Following an initial review, additional data requests or on-site inspections may then be initiated in a stepwise manner.

Figure 1 presents the remote inspection procedure applied to nuclear material and related facilities. The procedure is designed to detect anomalies through the integrated review of remotely collected safeguards surveillance data and operator-declared information. Once an anomaly is identified, an initial assessment is performed to determine whether it arises from equipment malfunction, communication disruption, or normal operational changes. Additional data review and cross-validation are then carried out. If the anomaly cannot be sufficiently resolved, or if a significant inconsistency is identified, the procedure transitions to on-site inspection and supplementary verification actions, thereby contributing to the restoration of CoK and improving the reliability of the overall verification conclusion.

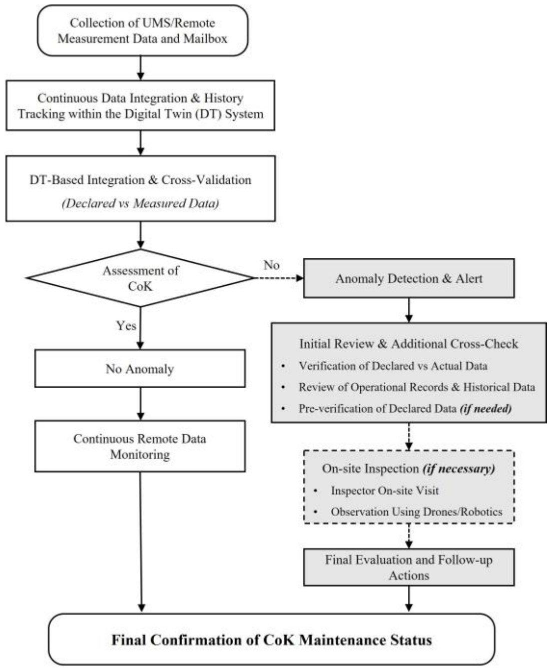

Figure 1 : Schematic Diagram of the Remote Inspection Procedure

This structure does not replace routine inspections. Rather, it operates as a complementary mechanism that provides monitoring and verification support between inspections. For example, during refueling operations in one module of a multi-module i-SMR, monitoring gaps may arise in other modules or unexpected fuel movements may be detected. In such cases, the framework can support a stepwise response, including additional data requests or follow-up on-site inspections, to reinforce verification.

For remote data to be formally used in safeguards verification, the following conditions must be satisfied: (1) assurance of data independence, (2) guarantees of integrity and temporal traceability, and (3) institutional arrangements for model validation and uncertainty management, together with verification of operational feasibility under practical implementation conditions.

Together with the proposed regulatory amendments, these technical and institutional conditions would provide a structured basis for integrating remote inspection into the national safeguards system.

4. Conclusion

This study suggests a regulatory direction for formally recognizing remote inspection within nuclear material accountancy in response to potential safeguards gaps associated with multi-module deployment and reduced operational staffing in i-SMR facilities.

By proposing amendments at the level of regulatory notice together with the necessary technical conditions for the use of remote data, this study clarifies how remote inspection can be incorporated into the existing safeguards system as a complementary inspection approach. The proposed approach does not replace routine inspections but supplements them within the existing inspection framework.

However, further institutional and technical validation is required before remote data can be formally used in safeguards verification. Future research will seek to develop concrete regulatory proposals by revising the Detailed Guidelines for Nuclear Material Accountancy Inspections.

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