IMPLEMENTATION OF RISK-INFORMED PERFORMANCE-BASED REGULATION AND ENHANCED INSPECTION PROGRAMS IN KOREA

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ABSTRACT

This paper presents Korea's ongoing transition toward a Risk-Informed Reactor Oversight System (K-ROP), with the primary objective of enhancing regulatory effectiveness by integrating risk insights into inspection processes and decision-making. The legacy inspection system, which relied heavily on scheduled evaluations during overhaul (OH) periods, proved insufficient in detecting latent risks and systemic vulnerabilities. These limitations prompted the development of a revised approach that allows inspections to be conducted both during and outside OH periods, enabling more flexible, timely, and risk-sensitive oversight of nuclear power plants. A central component of this transformation is the Significance Determination Process (SDP), a structured methodology for assessing the safety significance of inspection findings. Utilizing quantitative indicators such as the change in Core Damage Frequency (ΔCDF), the SDP facilitates consistent classification of findings into minor or more-than-minor categories, thereby guiding the prioritization of enforcement actions. Through pilot applications and large-scale retrospective reviews, the SDP has demonstrated its effectiveness in supporting both targeted regulatory attention and efficient resource allocation. Case studies illustrate how SDP-based assessments contribute to identifying structural deficiencies and procedural gaps that may otherwise remain undetected under conventional inspection methods. The broader application of SDP has been accompanied by the establishment of a centralized data management system to monitor inspection outcomes and track risk trends. These developments reflect a more proactive, transparent, and evidence-based regulatory paradigm. While K-ROP remains under phased development, its implementation signals a significant departure from deterministic oversight practices, aligning Korea's nuclear regulatory strategy with global best practices and enhancing its capacity to ensure long-term operational safety.

Keywords: Nuclear Safety, Risk-Informed Regulation, Inspection Framework, Significance Determination Process, Regulatory Oversight

I. INTRODUCTION

Over the past two decades, the global nuclear industry has progressively transitioned toward risk-informed and performance-based regulatory frameworks to enhance safety and operational efficiency. A notable example is the United States, where the Nuclear Regulatory Commission (NRC) implemented the Reactor Oversight Process (ROP) in 2000. This approach integrates probabilistic risk assessments to prioritize regulatory focus on areas with the highest safety significance, thereby improving the objectivity and predictability of oversight activities. Following the U.S. lead, countries such as Mexico, Taiwan, Spain, and Japan have adopted similar frameworks, aligning their regulatory practices with international standards and emphasizing the importance of risk-informed decision-making in nuclear safety [1].

In Korea, the traditional inspection system has been characterized by rigid schedules and a deterministic approach, primarily focusing on compliance during overhaul (OH) periods. This methodology has shown limitations in effectively identifying and mitigating potential risks, particularly those that may arise during normal operations. The Fukushima Daiichi nuclear accident in 2011 served as a critical turning point, highlighting the need for a more proactive and comprehensive regulatory approach. In response, Korea's Nuclear Safety and Security Commission (NSSC) initiated a series of reforms aimed at strengthening the nation's nuclear safety framework. These efforts were encapsulated in the Comprehensive Plans for Nuclear Safety, with the second plan covering 2017–2021 and the third plan extending from 2022–2026, both emphasizing the adoption of risk-informed oversight strategies [2].

To address these challenges and align with international best practices, Korea embarked on the development of a Risk-Informed Reactor Oversight Process (K-ROP). This initiative aims to establish a regulatory framework that systematically monitors and manages the safety of operating nuclear power plants using risk information. Key components of K-ROP include revising inspection methods to allow for evaluations during both OH periods and normal operations, integrating risk-based evaluation models such as the Significance Determination Process (SDP), and implementing pilot testing procedures tailored to domestic conditions. Through these measures, Korea seeks to enhance the effectiveness of its nuclear regulatory oversight, ensuring a higher level of safety and public trust in its nuclear energy program.

II. ONGOING DEVELOPMENT OF THE RISK-INFORMED OVERSIGHT SYSTEM IN KOREA

II.A. Project Initiation and Framework

In 2019, the Korea Institute of Nuclear Safety (KINS) launched the project titled “Establish Risk-Informed Reactor Oversight System”, aimed at developing both the technological basis and regulatory framework necessary for a system that can systematically monitor and manage the safe operation levels of nuclear power plants using risk information. This project consists of two major subprojects:

Subproject ①: Development of a Risk-Based Regulatory Framework

This subproject focused on establishing a domestic oversight system informed by international benchmarking. Drawing from the analysis of overseas case studies—particularly from countries that have implemented the ROP—the project developed a conceptual framework for Korea's own risk-informed oversight system. Key elements include a structured process comprising: monitoring, evaluation, and response, supported by improvements in inspection strategies and comprehensive safety assessments. Additionally, this subproject included the formulation of an improved regulatory inspection strategy and the design of a comprehensive evaluation process to assess the overall safety level of nuclear facilities more holistically and accurately.

Subproject ②: Development of MPAS Model and SDP Management System

In parallel, efforts were directed toward the development of the Multipurpose Probabilistic Analysis of Safety (MPAS) model and the Significance Determination Process (SDP) management system. The MPAS model supports structured planning and evaluation of maintenance activities, while the SDP management system enables risk-informed decision-making by quantifying the safety significance of inspection findings and supporting enforcement prioritization.

In terms of resource planning, the implementation of these two subprojects has been supported by a stable and consistent multi-year budget allocation. Between 2020 and 2026, Subproject ①, which focuses on the development of a risk-based regulatory framework, has been allocated an annual budget of $300,000, while Subproject ②, involving the development of the MPAS model and the SDP management system, has received $450,000 per year. The consistent funding structure reflects the long-term commitment of the KINS to systematically advance both the conceptual and operational dimensions of a risk-informed oversight system.

Together, these subprojects form the foundation for Korea’s transition toward a modern, risk-informed regulatory oversight structure tailored to its unique operational environment and safety culture.

II.B. Conceptual Overview of the Risk-Informed Oversight Process

The process integrates Monitoring, Assessment, and Response, and emphasizes public communication and transparency throughout.

(1) Monitoring

Monitoring involves both regular inspections and enhanced regulatory inspections, such as:

(i) Routine regulatory inspections including investigations of incidents and component failures
(ii) Supplementary or intensified inspections, triggered when potential safety concerns are suspected. The monitoring process provides the raw data and findings necessary to support further evaluation and decision-making.

(2) Assessment

The assessment phase consists of two key components:

(i) Performance Indicator Comparison: Actual safety performance data (Performance Indicators) are compared against predetermined threshold values to detect deviations or trends of concern.
(ii) SDP: Inspection findings and anomalies are evaluated based on their safety significance, determining the risk level associated with each issue.

Both assessment branches feed into a comprehensive evaluation, which synthesizes results from inspections and performance data.

(3) Response

When the assessment process identifies significant safety concerns, appropriate responses are initiated. These may include

(i) Strengthened inspections (targeted follow-up audits),
(ii) Administrative measures, such as enforcement actions,
(iii) Operational restrictions, including partial or full suspension of plant operations when safety margins are deemed insufficient. This response mechanism ensures that findings with higher risk implications are met with commensurate regulatory actions.

(4) Public Communication and Transparency

An essential supporting element of the oversight process is open communication with the public. This includes:

(i) Disclosure of information online,
(ii) Community outreach sessions to explain the regulatory framework and any identified risks to local residents. This aspect strengthens public trust in the regulatory system and reinforces accountability.

II.C. Revision of the Inspection System

The historical inspection system for nuclear power plants in Korea was originally designed to ensure that facilities operated in compliance with licensing standards and remained fit for continued operation. At its core, the system emphasized verification of plant performance through inspections conducted primarily during the licensee's Overhaul period (OH), which typically spanned two to three months. This timing limitation imposed constraints on the scope and depth of inspections. As a result, the regulatory activities were concentrated on performance checks of approximately 11 major facilities. From an initial list of about 57 inspection items in the early 2000s, the system expanded to cover around 100 items by 2012, reflecting increased regulatory expectations and complexity in plant operations.

However, over time, several limitations of the conventional inspection framework became apparent. Most significantly, the confined timing window during the OH period made it difficult to allocate sufficient time for thorough and balanced evaluations. This led to an excessive focus on whether systems met minimal technical standards, rather than on detecting latent vulnerabilities or degradation trends that could compromise long-term safety. Compounding the issue, document reviews and interviews with plant personnel also had to be conducted within this narrow timeframe, resulting in inefficiencies and logistical burdens for both regulators and operators.

Beyond temporal constraints, the system also struggled to adequately identify anomalies and vulnerabilities that may not yet manifest as technical noncompliance, but which could act as precursors to significant safety events. Despite institutional efforts - such as the establishment of regional regulatory offices and increases in inspection personnel - the existing system lacked a comprehensive mechanism to ensure consistent and risk-informed evaluations across all operational stages of nuclear power plants.

To address these shortcomings, a revised inspection approach has been proposed. The new strategy introduces comprehensive inspections that are no longer confined to the OH period but can also be performed during normal plant operation. This flexibility allows for more adaptive scheduling and timely response to evolving safety conditions. In addition, the revised model emphasizes in-depth inspections that enable systematic monitoring of plant conditions and identification of subtle indicators of risk or degradation. By incorporating such risk-informed strategies, the revised inspection system aims to enhance the overall effectiveness of regulatory oversight and better safeguard nuclear safety in a dynamic operating environment. Key distinctions between the traditional and revised systems are summarized in Table I.

TABLE I. Comparison Between the Past and Revised Inspection Systems

Category	Past Inspection System	Revised Inspection System
Purpose	Verify compliance with licensing standards and operational suitability	Monitor and manage safety levels using risk information
Scope of Items	Initially focused on 11 major facilities; expanded to ~100 items by 2012	Emphasis on both technical standards and potential vulnerabilities
Inspection Timing	Conducted during licensee's OH period (approx. 2–3 months)	Conducted during both OH and normal operation
Focus	Compliance with technical specifications	Identification of anomalies and precursors to safety degradation
Institutional Support	Expanded regional offices and staff, but limited integration of risk insights	Integrates risk-informed tools (e.g., SDP) and allows adaptation to real-time plant conditions

III. SDP IN THE ENHANCED INSPECTION FRAMEWORK

The introduction of the SDP plays a pivotal role in Korea’s transition toward a Risk-Informed Reactor Oversight System, particularly as it directly supports and enhances the newly revised inspection regime. Under the former system, regulatory inspections lacked formalized procedures for identifying and prioritizing items for in-depth examination. This absence led to reactive or ad hoc inspection practices, often driven by routine cycles rather than meaningful safety signals.

In contrast, the enhanced inspection framework integrates the SDP as a foundational mechanism for risk-informed decision-making. It allows inspectors to assess the safety significance of findings, thereby guiding the selection of specific areas or components for focused evaluation. By introducing quantifiable thresholds and structured criteria, SDP enables regulators to identify issues that may not immediately violate technical standards but nevertheless warrant close attention due to their potential to contribute to future safety degradation.

This functionality is particularly crucial in the Korean context, where inspection time and resources are limited. The revised system, which permits inspections during both the outage and operational periods, requires a method to triage inspection efforts efficiently and effectively. SDP fills this need by filtering findings and channeling regulatory attention to areas of elevated risk.

Moreover, by explicitly linking safety evaluations to risk metrics, such as ΔCDF (Change in Core Damage Frequency), the SDP strengthens the logical and empirical basis of regulatory responses. This reinforces the credibility and transparency of regulatory actions, which is essential for building public confidence and fostering a proactive safety culture among plant operators.

In sum, the SDP does not function in isolation; it is tightly coupled with the broader structural reform of Korea’s regulatory oversight system. It transforms the inspection process from a static checklist exercise into a dynamic, risk-informed safety assurance mechanism—one that supports targeted, evidence-based inspections and aligns with global best practices for reactor oversight.

III.A. Significance Determination Process

III.A.1. Definition and Identification of Performance Deficiency

The first step in the SDP is determining whether a Performance Deficiency (PD) exists. A PD is identified when an issue satisfies both of the following conditions:

(i) The issue involves a failure to meet a regulatory requirement or safety standard.
(ii) The issue was within the licensee's reasonable ability to foresee and correct, and therefore, it should have been prevented.

If both criteria are not met, the issue is categorized as a minor concern and does not proceed further in the SDP.

III.A.2. Screening for Safety Significance: "More-than-Minor" Evaluation

When a PD is confirmed, it is further evaluated to determine if it is "More-than-Minor", a classification that triggers detailed safety significance analysis. To be considered more-than-minor, the PD must meet at least one of the following conditions:

(i) It could reasonably be viewed as a precursor to a significant safety event.
(ii) If left uncorrected, it has the potential to lead to a more serious safety concern.
(iii) It is associated with a cornerstone objective (e.g., reactor safety, barrier integrity), and adversely affects that objective.

This screening step is essential to prioritize regulatory attention and resources on findings with potential safety consequences.

III.A.3. Application of the SDP Model

Once a finding is determined to be more-than-minor, it is subject to risk-informed evaluation through the SDP. This process uses metrics such as ΔCDF to quantify risk. The ΔCDF is calculated based on the increase in core damage probability due to a failure or deficiency, adjusted for the time duration the issue persisted during a year [3]. This quantitative approach allows regulators to consistently grade the severity of findings and determine the corresponding enforcement action or follow-up inspection intensity.

III.A.4. Cross-Cutting Aspects and Final Classification

The SDP also considers cross-cutting aspects such as human performance, safety culture, and organizational decision-making. By mapping findings to broader regulatory cornerstones and objectives, the process ensures a comprehensive understanding of systemic vulnerabilities. Final significance classifications are recorded in structured formats to inform corrective action planning, operator feedback, and performance trend analysis.

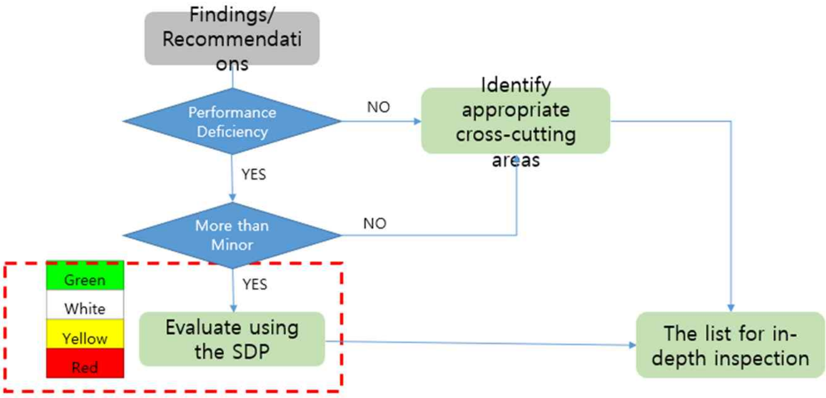

FIGURE 1. Process for Selecting In-Depth Inspection Items Using SDP

III.B. Case Studies

To illustrate the practical application of the SDP, this section presents two representative inspection cases. These examples highlight how SDP enables regulators to distinguish between issues requiring strong enforcement actions and those manageable with corrective measures, based on safety significance.

III.B. 1. Structural Deficiencies in Safety-Related Components

During an inspection of a nuclear power plant, several deficiencies were identified in structures critical to maintaining reactor safety. Specifically, corrosion was observed on the anchor bolts of a Seismic Category I condensate water storage tank, but no repair measures had been taken. In addition, loose or missing bolts were found on 24 structural brackets inside the containment building during the 14th outage inspection, and again, no corrective actions had been implemented. Lastly, cracks were discovered in the sealing material of a Component Cooling Water (CCW) penetration (PY3121), which had not been periodically maintained.

These findings met the criteria for a performance deficiency, as they involved failure to comply with established maintenance standards and were within the licensee's ability to prevent. Further evaluation revealed that, while these issues had not yet led to a significant incident, they posed a credible risk to barrier integrity, a key safety cornerstone. Additionally, if left unaddressed, the deficiencies could degrade the plant's defense-in-depth capabilities and potentially lead to more severe safety concerns.

Accordingly, the issue was classified as More-than-Minor, and the licensee was required to perform an integrity assessment of the affected components, implement targeted repairs, and establish preventive measures to avoid recurrence.

III.B. 2. Inadequate Qualification of Visual Examiner

In another instance, an inspection team identified that a visual examination of the secondary side of the steam generator had been carried out by a technician who lacked the proper certification. The areas examined included critical components such as the moisture separator, steam dryer, downcomer feedring, and recirculation feedring.

The inspection finding was indeed a performance deficiency, as it involved noncompliance with qualification standards. However, upon evaluation using the SDP, the issue did not meet any of the thresholds for classification as More-than-Minor. There was no evidence that the lack of certification contributed to inspection inaccuracies, nor did the finding affect a cornerstone objective or present a significant precursor to a safety event.

Consequently, the issue was deemed Minor, and the recommended corrective action was to re-conduct the inspection using a properly certified examiner and to implement internal checks to prevent future occurrences.

These case studies underscore the value of the SDP in ensuring that regulatory responses are proportionate to the actual risk posed. By providing a structured pathway from finding identification to enforcement decision, the SDP enhances both the efficiency and the integrity of Korea's evolving nuclear oversight system.

III.C. Scaling Up: Broad Application and Data Management of the SDP

In addition to individual inspection cases, the KINS has systematically applied the SDP across a broad set of historical and recent inspection data. In 2023, SDP evaluations were conducted for 27 issues identified at a specific nuclear power plant, marking one of the first extensive applications of the process in a real-world operational context.

Building on this experience, a large-scale retrospective review was initiated in 2024. This involved the examination of all inspection findings reported between 2013 and 2023 across Korea's operating NPPs. As part of this effort, SDP evaluations are being carried out at a pace of approximately 100 cases per month, demonstrating the scalability and practicality of the process.

To manage this growing body of data, KINS has maintained a dedicated database system, which serves as a centralized repository for tracking inspection findings, their associated risk significance levels, and follow-up actions. This structured information management supports trend analysis, regulatory decision-making, and continuous improvement of the oversight system.

These ongoing efforts reflect a proactive and systematic approach to embedding SDP into the regulatory workflow, further aligning Korea's reactor oversight practices with international standards.

IV. CONCLUSIONS

This paper presented Korea's ongoing efforts to transition toward a Risk-Informed Reactor Oversight System, emphasizing the integration of risk insights into inspection processes and regulatory decision-making. Recognizing the limitations of the legacy inspection framework - such as its rigidity, limited timing, and insufficient ability to detect latent risks - KINS has launched a multi-faceted initiative to reform its oversight model.

At the core of this initiative lies the SDP, which provides a structured and risk-based method to evaluate inspection findings. Through carefully defined criteria and quantitative risk indicators such as ΔCDF, the SDP enables regulators to distinguish between minor and more-than-minor performance deficiencies [4], ensuring that enforcement actions are appropriately prioritized. Case studies have demonstrated how this process supports both safety assurance and regulatory efficiency by targeting high-risk conditions without overburdening operators.

Beyond individual case applications, the SDP is being systematically scaled up. Evaluations have been conducted not only for recent findings but also for inspection records spanning a decade, with results organized into a centralized data management system. This expansion underscores the practicality and scalability of the framework, reinforcing its role as a cornerstone of the future oversight model.

While the K-ROP has not yet been fully implemented, the foundational work completed to date - development of the regulatory framework, revision of inspection programs, establishment of evaluation tools, and pilot-scale data applications - represents a significant leap toward a modern, transparent, and risk-informed regulatory paradigm. Continued effort in refining the system, supported by international benchmarking and stakeholder engagement, - through international benchmarking, operator engagement, and policy alignment - will be critical to achieving a sustainable regulatory model for the future.

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