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Comparative Analysis of Diversion Pathway Analysis Methodologies for Safeguards-by-Design Implementation

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1. Introduction

With the anticipated introduction of new nuclear facilities in the Republic of Korea—such as interim spent fuel storage facilities and SMRs—and following international trends, there is a growing need to apply Safeguards-by-Design (SBD) measures at the design stage. However, because legal and technical bases for safeguards regulations at the design stage are lacking domestically, developing methodologies to implement IAEA safeguards in new nuclear facilities has become an urgent priority.

Accordingly, this study aims to identify the optimal approach by comparing various diversion/acquisition pathway analysis methodologies developed to enhance safeguards' applicability and efficiency in new nuclear facilities.

Nuclear technology is derived from nuclear weapons development, and there is always the possibility of unauthorized diversion or illegal acquisition of nuclear material at any stage of the fuel cycle. In order to minimize this risk, numerous methodologies for analyzing diversion pathways and acquisition pathways have been developed. This study conducts an in-depth comparative analysis of these approaches—focusing primarily on the IAEA's PRADA (Proliferation Resistance: Acquisition/Diversion Pathway Analysis) methodology, the Generation IV International Forum (GIF) PRPP (Proliferation Resistance & Physical Protection) methodology, and more recent domestic proposals—and derives relevant insights.

2. Concept of Diversion/Acquisition Pathways

A "diversion pathway" generally refers to a scenario in which nuclear material or facilities subject to safeguards are diverted unauthorizedly. A typical example would be a state covertly diverting nuclear fuel or source material under international safeguards for a weapons program. By contrast, an "acquisition pathway" is a broader concept encompassing all possible routes by which weapons-usable nuclear material could be obtained. It includes diversion and clandestine production at new secret facilities, illegal procurement (smuggling, purchases), and other means. As suggested by the name of the IAEA's PRADA project, "acquisition/diversion pathway analysis" is about systematically identifying and assessing all potential strategies and means by which a state could acquire material suitable for nuclear weapons.

In short, diversion pathway analysis primarily focuses on how nuclear material or facilities—legally in operation under safeguards—could be covertly removed and diverted, usually emphasizing scenarios in which a state misappropriates materials from an existing peaceful program. Acquisition pathway analysis, on the other hand, encompasses all possible routes at the national level for obtaining nuclear weapons, including building secret new facilities, acquiring specialized nuclear technology and equipment, and breaching international norms. It is thus considered a higher-level concept that includes diversion pathway analysis. While diversion pathway analysis concentrates on individual facilities or material flows, acquisition pathway analysis addresses a nation's overall strategy for weaponization.

This distinction is significant depending on the assessment objective. Under the international safeguards regime, the key concern is the possibility of diversion within a specific facility and the likelihood of detecting it. Conversely, a more macro-level scenario of acquisition routes must be considered for national nonproliferation policies or technology development. The PRADA methodology covers diversion and acquisition pathways, conducting scenario analyses that include a state's technological capabilities and motivations. Meanwhile, the GIF PRPP methodology also defines multiple threat categories—such as diversion or misuse by a state, breakout after withdrawal from treaties, and theft or sabotage by non-state actors—thus incorporating the acquisition pathway concept.

In summary, diversion pathway analysis mainly asks, from a safeguards perspective, "How can nuclear material be removed?" while acquisition pathway analysis, from a broader nonproliferation perspective, asks, "How can a weapons program be realized?" These two concepts differ in scope yet share the overarching goal of preventing the misuse of nuclear materials.

3. Major Methodologies in Comparison

3.1 IAEA PRADA (Proliferation Resistance: Acquisition/Diversion Pathway Analysis)

(Background)

- Developed as part of the IAEA's INPRO project to evaluate the potential for nuclear weapons diversion within innovative nuclear energy systems (INS) in advance.
- It encompasses not only diversion pathways but also national-level acquisition pathways, identifying "acquisition/diversion pathways" and assessing the use of both "intrinsic" and "extrinsic" barriers.

(Analytical Procedure)

- Define threat scenarios (including state capabilities and motivations).
- Set boundaries for the target system.
- Identify proliferation targets (nuclear material, technology).
- Derive potential diversion or acquisition pathways for each stage of the process.
- Evaluate the radiological barriers, safeguards, physical security applied to each pathway.
- Conduct detailed logical analysis (event trees, success/failure trees) for pathways of high concern.
- Integrate results and propose improvements.

(Key Features)

- Primarily, it focuses on qualitative assessments, considering national institutions and political contexts.
- The core indicator is whether multiple barriers are implemented.
- Its utility has been demonstrated in application to the DUPIC fuel cycle (a Korea-led research project).

3.2 GIF PRPP (Proliferation Resistance & Physical Protection)

(Background)

- Developed by the Generation IV International Forum (GIF) to integrate proliferation resistance and physical protection from the design stage of Gen-IV reactors.
- Proliferation Resistance (PR) aspects use six measures: technical difficulty, cost, time required, material characteristics, detection probability, and detection resource efficiency.
- Physical Protection (PP) aspects use three measures: the probability of an attack's success, the consequences of such an attack, and resources for protection.
- Covers threats at the state level (covert diversion, breakout, clandestine facilities) and non-state (theft, sabotage).
- A tool called PRCALC was developed to analyze PRPP evaluation factors quantitatively.

(Analytical Procedure)

- Define threat scenarios (illegal acquisition of nuclear material—diversion, misuse, theft—and physical attacks, such as sabotage), then analyze pathways.
- Construct a Markov model representing state transitions within each component of the nuclear system based on the defined threat pathways.
- Set model parameters (Detection Time, Anomaly Detection/Verification Time, Uncertainty, Intrinsic Barriers).
- Use the Markov model to calculate results, including Detection Probability, Technical Failure Probability, Success Probability, Proliferation Time, Proliferation Cost, and Detection Resource Efficiency.

(Key Features)

- Pathways are defined for each scenario, and metrics (difficulty, time, cost) are assessed semi-quantitatively.
- It can be broadly applied to multiple nuclear fuel cycles (open cycle, PUREX, UREX, ESFR), enabling diverse evaluations.
- PRCALC provides comprehensive proliferation resistance and physical protection (PR&PP) indicators (detection probability, technical difficulty, time, resource efficiency, diversion cost, material type).
- The model accounts for measurement errors, tolerance levels, and false alarms, capturing uncertainties likely to arise in real-world conditions.

3.3 Development of an Event-Tree-Based Diversion Pathway Generation Program

(Background)

- Developed domestically in preparation for introducing new nuclear facilities (interim spent fuel storage, SMRs), aiming to establish a technical standard for applying safeguards regulations at the design stage.

(Analytical Procedure)

- Collect facility operational (process) information: Gather detailed operational data to examine the potential for diversion.
- Analyze unit operations (processes): Break down each process unit of the facility and collect fundamental information for diversion assessment.
- Generate diversion pathways from unit operations: Based on each process unit, consider the location and form of nuclear material and possible diversion

strategies. Use event and fault trees to generate diversion pathways.

- Risk analysis and evaluation of each diversion pathway: For each generated pathway, use success and failure trees to calculate detection probabilities and diversion success probabilities, then assess relative risk.
- Compile and document results: Systematically organize the evaluation results into documentation that provides guidelines usable by regulators and designers.

(Key Features)

- Systematic tree-based approach: A combined event tree and fault tree analysis framework derive diversion pathways and quantitatively analyze detection and success probabilities.
- Detailed components of diversion pathways: Factors such as material attractiveness, diversion amount, record manipulation, removal manipulation, and number and roles of accomplices are considered to enable a more granular, realistic analysis.
- Relative risk assessment: Emphasizes comparing detection probabilities on a relative basis, identifying which pathways are most vulnerable within a facility, and prioritizing the reinforcement of safeguards accordingly.
- Automated program development: A prototype program is developed to automatically generate diversion pathways from user input and derive minimal path sets, thereby quickly providing results.

4. Conclusions

Diversion pathway and acquisition pathway analyses are essential tools for proactively evaluating and strengthening the nonproliferation robustness of nuclear energy systems. Although the methodologies introduced in this study evolved in different contexts, they aim to identify and block any potential pathways for nuclear weapons development through multiple barriers.

However, more standardized methodologies are needed to effectively apply safeguards-by-design in regulatory practice. In particular, it is crucial to analyze the entire nuclear fuel cycle at the national level while also evaluating how newly introduced individual facilities might affect this broader cycle. Furthermore, it is necessary to identify potential scenarios and pathways for diversifying nuclear material within a facility and preemptively assess the applicability of various safeguards measures.

It should be noted that, at their core, all these approaches rely on expert judgment and scenario assumptions; none can be objective. Nevertheless, the analytical process significantly enhances nonproliferation, underscoring the importance of ongoing and active discussion.

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