[PO11B17] Comparative Analysis of Acquisition/Diversion Path Analysis Methodologies for Safeguards-by-Design Implementation

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Introduction

- The anticipated introduction of new nuclear facilities in the Republic of Korea, including interim spent fuel storage facilities and small modular reactors (SMRs), necessitates the implementation of Safeguards-by-Design (SBD) measures during the design stage. This requirement aligns with international trends, underscoring the importance of comprehensive safeguards in the nuclear energy sector. Nevertheless, given the absence of both legal and technical foundations for safeguards regulations during the design stage, the development of methodologies for implementing IAEA safeguards in new nuclear facilities has become a matter of urgent priority.
- Accordingly, the objective of this study is to ascertain the most efficacious approach by comparing various acquisition path analysis methodologies developed to enhance the applicability and efficiency of safeguards in new nuclear facilities.
- The development of nuclear technology is rooted in the development of nuclear weapons. Consequently, there is always the possibility of unauthorized diversion or illegal acquisition of nuclear material at any stage of the fuel cycle. A multitude of methodologies have been developed for the purpose of analyzing diversion and acquisition pathways, with the objective of minimizing the aforementioned risk. This study conducts an exhaustive comparative analysis of the aforementioned approaches, with a primary focus on the International Atomic Energy Agency's (IAEA) PRADA (Proliferation Resistance: Acquisition/Diversion Pathway Analysis) methodology, the Generation IV International Forum's (GIF) PRPP (Proliferation Resistance & Physical Protection) methodology, and more recent domestic proposals. The study derives pertinent insights from these analyses.

APA Approach (Acquisition Path Analysis)

Definition and Purpose of an Acquisition Path Analysis in IAEA Safeguards

- Acquisition Path Analysis (APA) is defined as "the analytical process of identifying and evaluating all plausible technical means that a state might consider to acquire nuclear material for the manufacture of nuclear weapons or other nuclear explosive devices." This analytical process constitutes a fundamental component of the state-level safeguards approach, thereby serving as the basis for the International Atomic Energy Agency's (IAEA) development of customized safeguards strategies tailored to the specific needs of individual nations.
- The International Atomic Energy Agency (IAEA) has developed a range of policies and approaches to ensure the non-proliferation of nuclear materials. In particular, Acquisition Path Analysis (APA) is a core element of the State Level Approach (SLA) and plays an important role in the effective implementation of the nuclear nonproliferation regime.

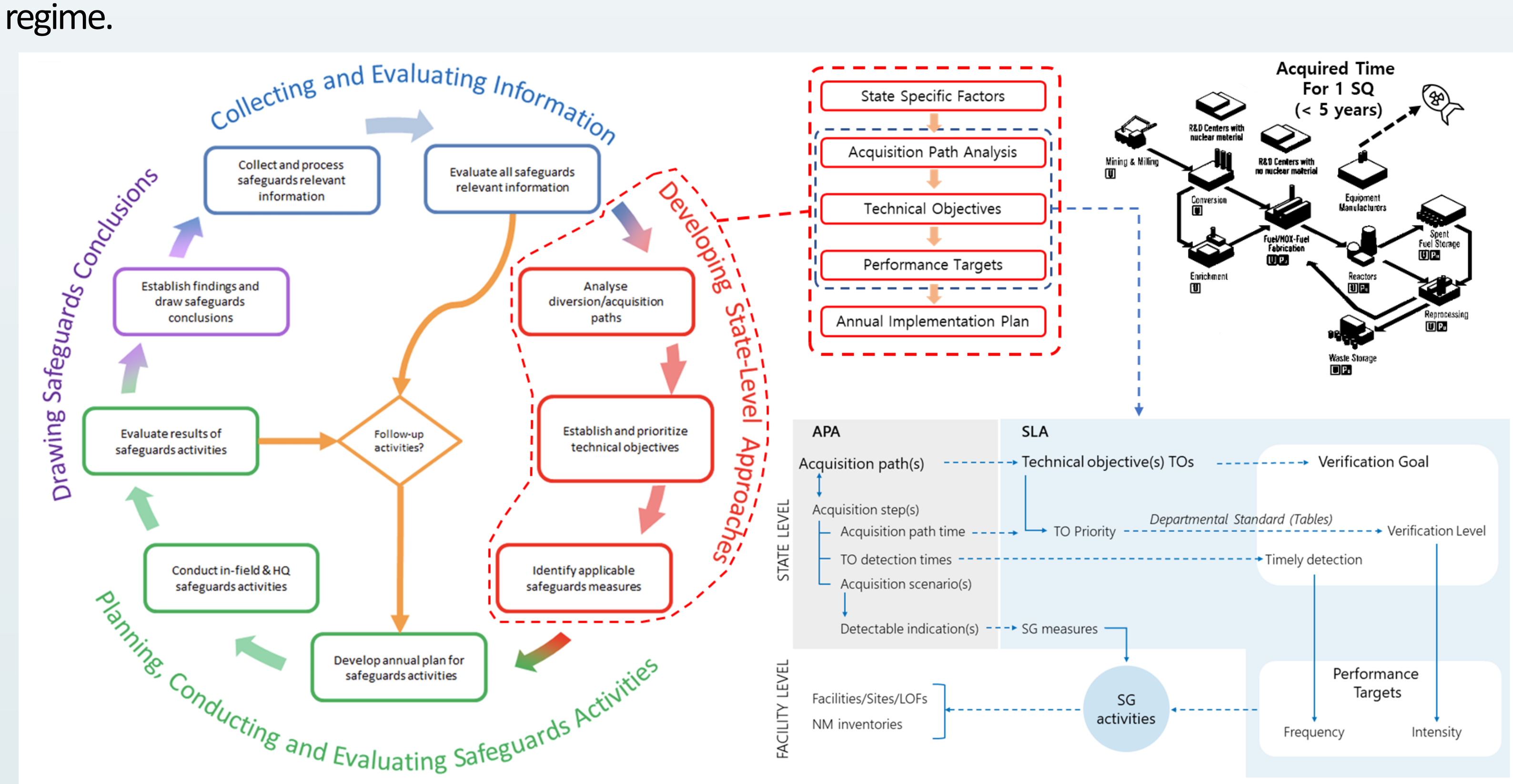

Figure 1. Acquisition Path Analysis in the IAEA SLA

- The Acquisition Path is defined as "a series of processes that a country must undertake to obtain weapons-grade nuclear material." The following five scenarios are possible components of this acquisition path:
  - P: Indigenous production of pre-34(c) nuclear material;
  - D: Diversion of declared nuclear material in declared facilities or LOFs;
  - M: Undeclared production or processing of nuclear material in declared facilities or LOFs;
  - F: Undeclared production or processing of nuclear material in undeclared facilities; or
  - I: Undeclared import of nuclear material.
- The primary objective of the APA is to methodically analyze all potential pathways and identify the most viable option for a state to acquire nuclear material for nuclear weapons. This analysis enables the IAEA to effectively allocate its safeguards resources and efforts.

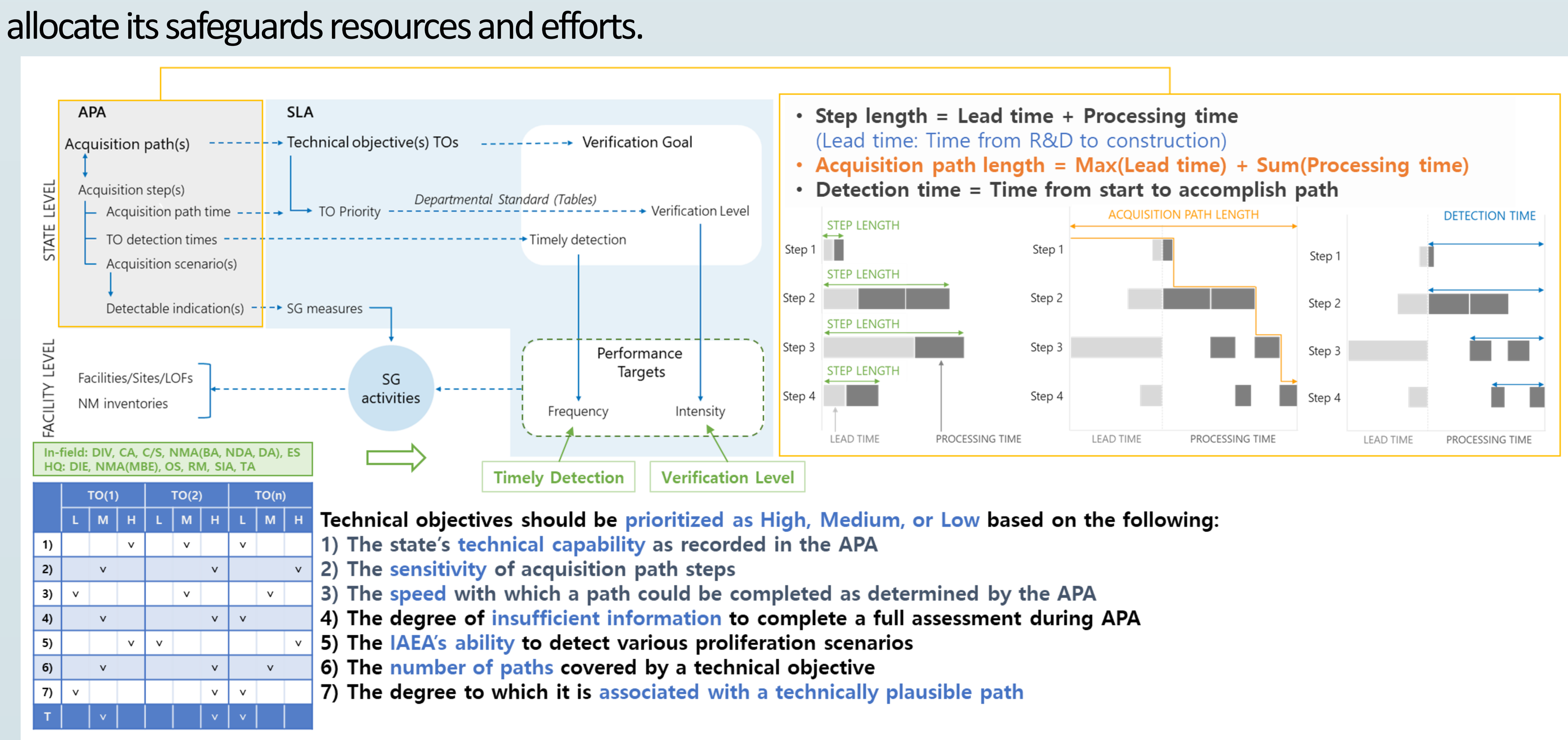

Figure 2. The Performance Targets Setting Process in IAEA APA

A comparison of the major methodologies

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).

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.

Diversion Path Generation Algorithm to Apply to the Safeguards Analysis

(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.

Conclusions

- Dedicated Path Analysis and Acquisition Path Analysis are considered to be fundamental tools for preemptively evaluating and strengthening the nuclear nonproliferation integrity of nuclear systems. The methodologies mentioned in this study were developed in different contexts, yet they all share the common objective of "identifying potential pathways for nuclear weapon development and sealing them off with multiple barriers." These systems are of particular significance in that they evaluate nuclear systems planned for future implementation by applying the concept of design-based safety measures.
- However, given that the IAEA's safety measures necessitate an integrated evaluation at the national level rather than at the facility level, the aforementioned methodologies are inherently constrained. Consequently, there is a pressing need for enhanced methodologies capable of evaluating national-level nuclear systems. Moreover, there is an imperative for more systematic analysis and application of the IAEA's APA.
- Despite the inherent subjectivity of the reviewed approaches, stemming from their basis in expert judgment and scenario assumptions, the analysis of these approaches is nevertheless instrumental in the enhancement of nuclear non-proliferation efforts. It is imperative that such discussions be conducted with greater frequency.

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