Establishing Antineutrino-Based Safeguards for Advanced Nuclear Reactors Using the State-Level Concept

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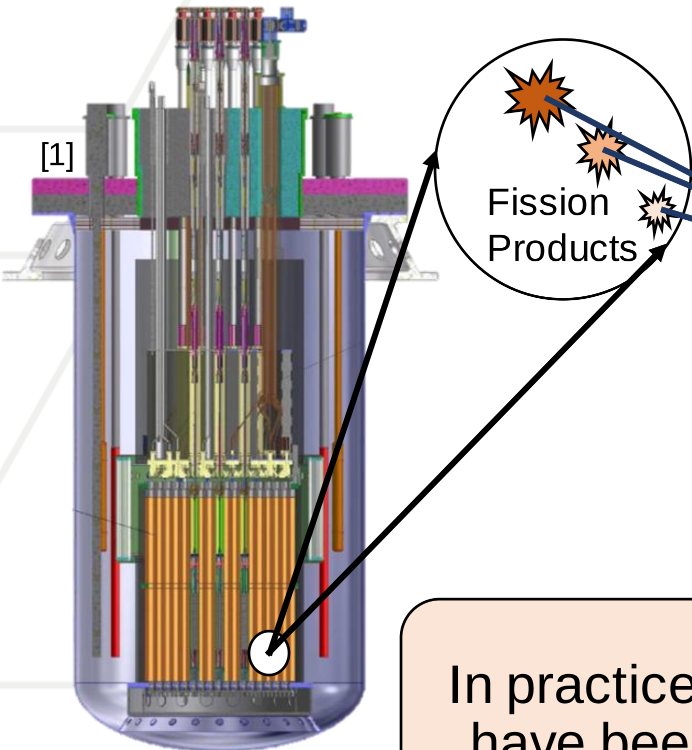
Introduction

In theory, antineutrino detection systems can be used to support many safeguards objectives



Inventory Verification

Power Verification

On/Off Verification

Antineutrinos

In practice, antineutrino detection systems have been studied for specific scenarios

To what extent are case study scenarios and assumptions aligned with IAEA technical objectives?

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Motivation

To what extent are case study scenarios and assumptions aligned with IAEA technical objectives?

Virtually Not Plausible:
Case studies demonstrating a significant system for an insignificant scenario

Virtually Not Possible:
Case studies demonstrating an insignificant system for a significant scenario

Exaggerated Example:
On/Off Verification for a Reactor Hall of Small Modular Reactors (SMRs)

- 2 SMRs
- A 3-month collection period
- A required 20% detection probability

Exaggerated Example:
Diversion detection of Special Nuclear Material (SNM) in Generation-IV reactors

- Diverted from every assembly
- Enriched replacement fuel
- A reactor operator advisory
- A required 90% detection probability

We want a **straightforward** and **transparent** method to select misuse/diversion scenarios while assigning **plausible** and **possible** detection objectives

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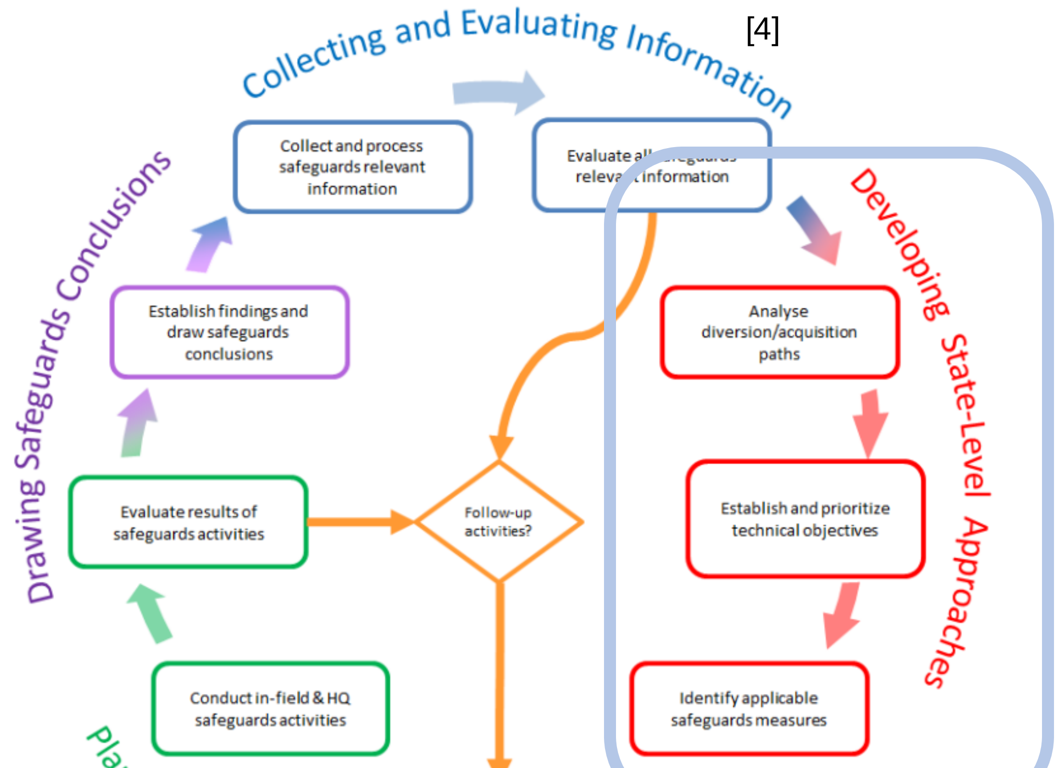
The Current IAEA Safeguards Framework

[3]

State-Level Concept (SLC):
The general notion of implementing IAEA safeguards in a manner that considers a State's nuclear and nuclear related activities and capabilities as a whole, within the scope of the safeguards agreement.

[4]



[3]

State-Specific Factors (SSFs): The six objective safeguards relevant factors that are particular to a State which are used by the IAEA Secretariat in the development of a State-level safeguards approach (SLA) and in the planning, conduct and evaluation of safeguards activities for that State. The SSFs are based on **factual information and are objectively assessed.**

Technical Approach

Scenario Selection

- Diverted Assemblies
- Replacement Fuel Enrichment
- Masking Thermal Reactor Power
- …

Use State-Specific Factors (SSFs) to guide antineutrino-based safeguards development for practical IAEA implementation

- Significant Quantities
- Detection Time
- Detection Probability (DP)
- False Alarm Probability

Quantitative Feedback

Detection probabilities are based on the premise that the State's ability to convert the material to nuclear weapons cannot be ruled out, and are set at high (90%), medium (50%) or low (20%), depending on the type of material and the inspection purpose[2].

Independent SSF Consideration

[3] SSF-1: The type of safeguards agreement in force for the State and the nature of the safeguards conclusion drawn by the IAEA.

Scenario Selection

Comprehensive Safeguards Agreement (CSA)	CSA and Additional Protocol (AP)	CSA, AP, and Broader Conclusion
DP = 0.9	DP = 0.5	DP = 0.2

Quantitative Feedback

SSF-1 | SSF-2 | SSF-3 | SSF-4 | SSF-5 | SSF-6

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Independent SSF Consideration

[3] SSF-2: The nuclear fuel cycle and related technical capabilities of the State.

Scenario Selection

Fuel enrichment and reprocessing	Fuel enrichment or reprocessing	Neither fuel enrichment nor reprocessing
DP = 0.9	DP = 0.5	DP = 0.2

Quantitative Feedback

SSF-1 SSF-2 SSF-3 SSF-4 SSF-5 SSF-6

Independent SSF Consideration

[3] SSF-3: The technical capabilities of the State (or regional) system of accounting for and control of nuclear material (SSAC/RSAC).

Scenario Selection

Low Confidence in State Reporting	Limited Confidence in State Reporting	Confident in State Reporting
DP = 0.9	DP = 0.5	DP = 0.2

Quantitative Feedback

SSF-1 SSF-2 SSF-3 SSF-4 SSF-5 SSF-6

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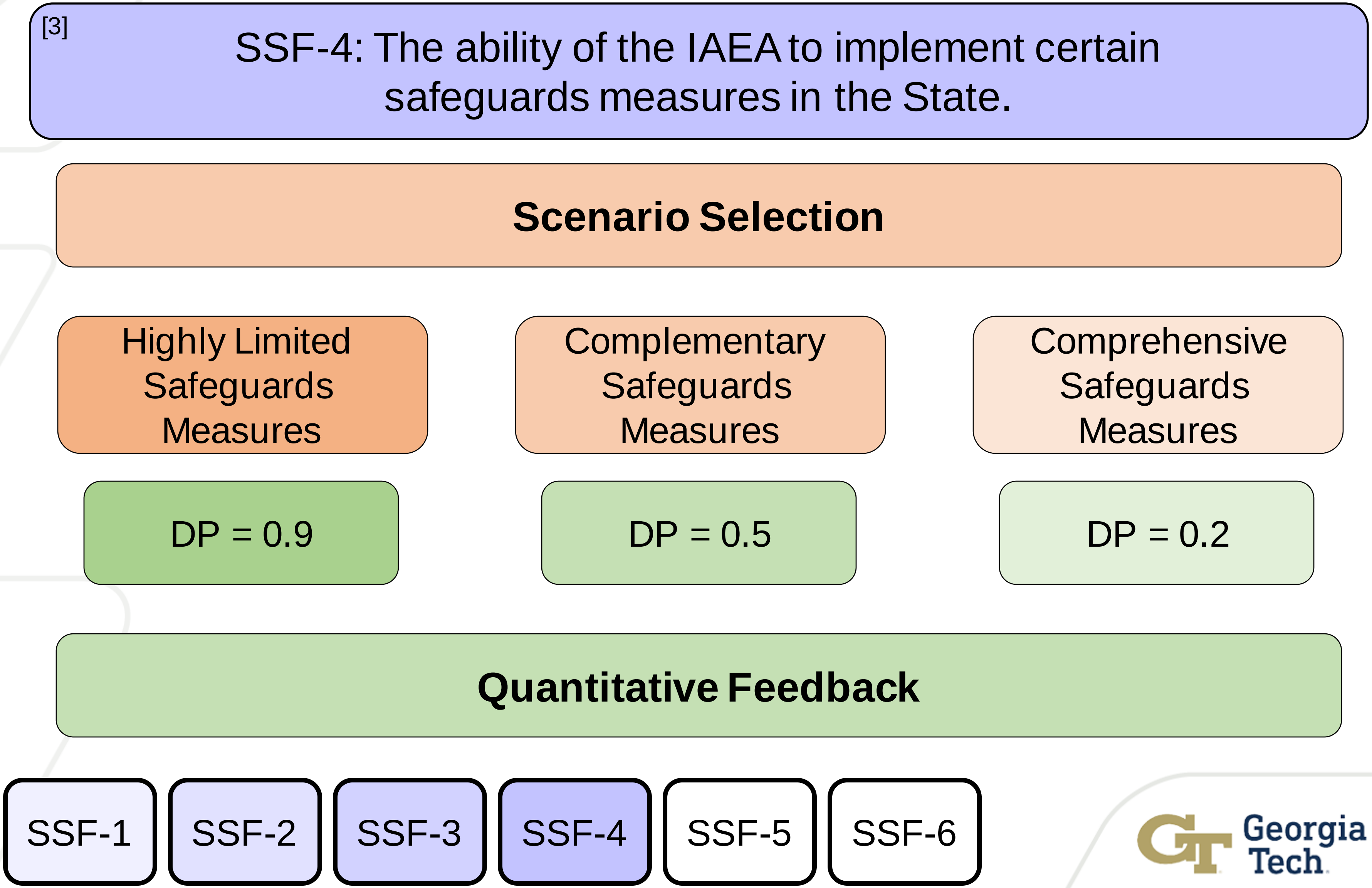
Independent SSF Consideration



Independent SSF Consideration

[3] SSF-5: The nature and scope of cooperation between the State and the IAEA in the implementation of safeguards.

Scenario Selection

Limited Cooperation	Partial Cooperation	Strong Cooperation
DP = 0.9	DP = 0.5	DP = 0.2

Quantitative Feedback

SSF-1 SSF-2 SSF-3 SSF-4 SSF-5 SSF-6

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Independent SSF Consideration

[3] SSF-6: The IAEA's experience in implementing IAEA safeguards in the State.

Scenario Selection

Limited or Historically Failed Safeguards Requirements	Historically Meet Safeguards Requirements	Historically Exceed Safeguards Requirements
DP = 0.9	DP = 0.5	DP = 0.2

Quantitative Feedback

SSF-1 | SSF-2 | SSF-3 | SSF-4 | SSF-5 | SSF-6

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Balancing State-Specific Factors

$DP_{Scenario}$ = f($DP_{SSF\text{-}1}$ $DP_{SSF\text{-}2}$ $DP_{SSF\text{-}3}$ $DP_{SSF\text{-}4}$ $DP_{SSF\text{-}5}$ $DP_{SSF\text{-}6}$)

The State Evaluation Group's utilization of custom State-Specific Factors are in **Internal Documents**

$$DP_{Scenario} = \alpha * DP_{SSF\text{-}1} + \beta * DP_{SSF\text{-}2} + \gamma * DP_{SSF\text{-}3} + \delta * DP_{SSF\text{-}4} + \varepsilon * DP_{SSF\text{-}5} + \zeta * DP_{SSF\text{-}6}$$

Where α, β, γ, δ, ε, and ζ sum to 1 and can be customized by researchers to focus on strengthening targeted portions of the State-Level Approach

Final values can be determined by the IAEA Department of Safeguards to effectively compare "apples and oranges"

SSF-1 SSF-2 SSF-3 SSF-4 SSF-5 SSF-6

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Guiding a Case Study

$$DP_{Scenario} = \alpha*DP_{SSF-1} + \beta*DP_{SSF-2} + \gamma*DP_{SSF-3} + \delta*DP_{SSF-4} + \varepsilon*DP_{SSF-5} + \zeta*DP_{SSF-6}$$

We assume the IAEA will only establish antineutrino-based safeguards for States

- under the broader conclusion ($\alpha = 0$)
- with capable SSACs ($\gamma = 0$)
- with strong cooperation ($\varepsilon = 0$)

We assume the IAEA will put less of a priority on a State's historical experience implementing safeguards considering minimal experience in an advanced nuclear reactor scenario ($\beta = 0.4$, $\delta = 0.4$, $\zeta = 0.2$)

Fuel enrichment and reprocessing ($DP_{SSF-2} = 0.9$)

Highly Limited Safeguards Measures ($DP_{SSF-4} = 0.9$)

Historically Meet Safeguards Requirements ($DP_{SSF-6} = 0.5$)

$$DP_{Scenario} = 0.82$$

Conclusions

A **transparent methodology** has been created

SSF-1 | SSF-2 | SSF-3 | SSF-4 | SSF-5 | SSF-6

to propose **possible use cases**

Diverted Assemblies | Replacement Fuel Enrichment | Masking Thermal Reactor Power

with **plausible sensitivity goals**

$$DP_{Scenario} = \alpha * DP_{SSF\text{-}1} + \beta * DP_{SSF\text{-}2} + \gamma * DP_{SSF\text{-}3} + \delta * DP_{SSF\text{-}4} + \varepsilon * DP_{SSF\text{-}5} + \zeta * DP_{SSF\text{-}6}$$

to **strengthen IAEA safeguards**

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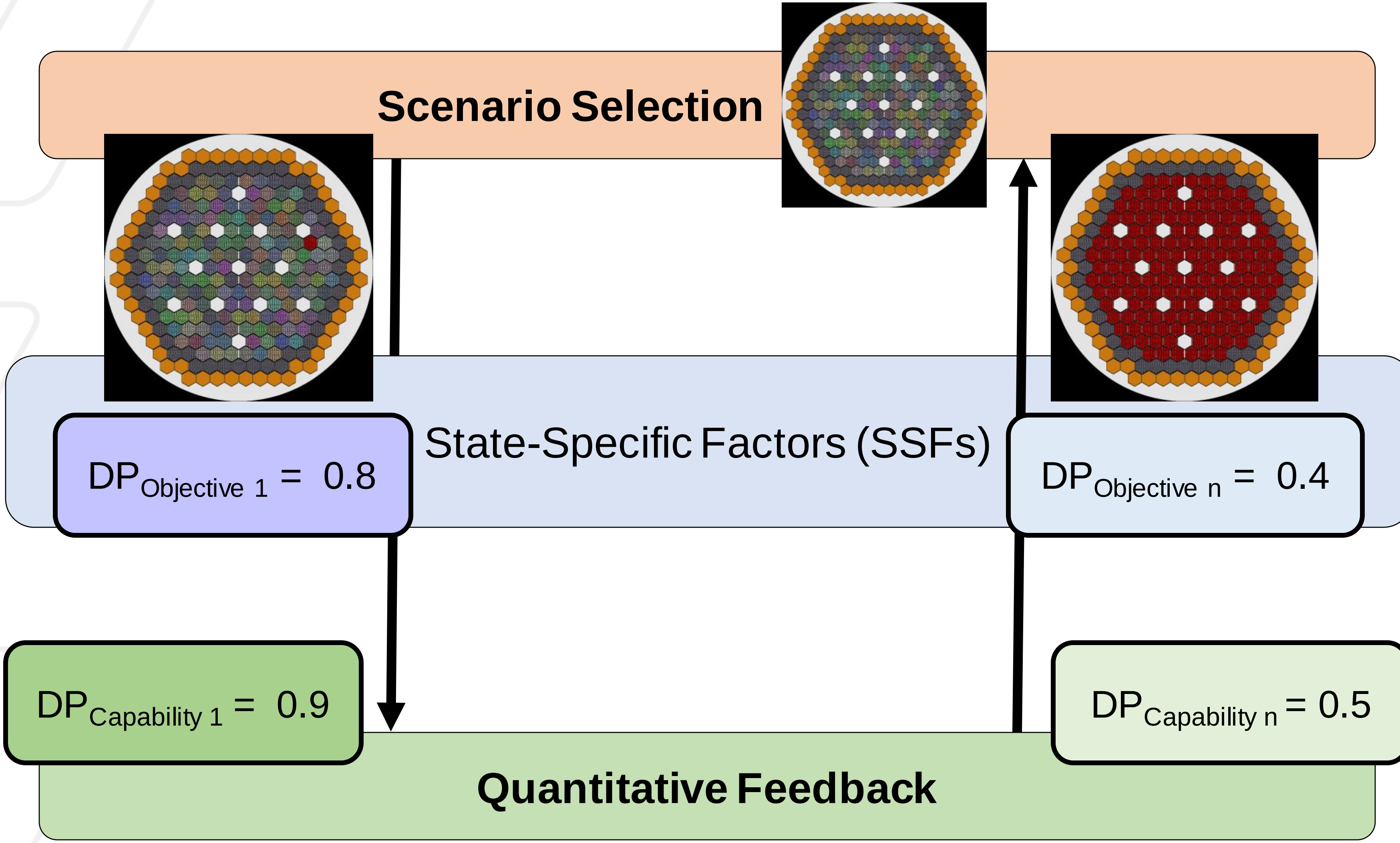
Future Work – Temporal Difference Learning



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Extra Slides

[4]

Establishing Safeguards – A General Guide

State Evaluation Group (SEG): A group within the IAEA's Department of Safeguards which evaluates all safeguards relevant information available to the IAEA about a State and […] performs acquisition path analysis, develops a State-level safeguards approach (SLA) and prepares an annual implementation plan (AIP) for individual States[3].

1. Conduct Acquistion Path Analysis: A structured method used to analyse the plausible paths by which, from a technical point of view, nuclear material suitable for use in a nuclear weapon or other nuclear explosive device could be acquired[3].

2. Establish Technical Objectives: The IAEA seeks to address the technical objectives to detect and deter any proscribed activity along a possible acquisition path or diversion path. […] The prioritization of technical objectives aims at the concentration of safeguards effort on areas of greater safeguards significance[3].

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[4]

Establishing Safeguards – A General Guide

3. Set Performance Targets: The degree to which a technical objective should be addressed in a State-level safeguards approach (SLA) (e.g. the required detection probability for the diversion of 1 significant quantity (SQ) of nuclear material within a period of time). Safeguards measures and safeguards activities, along with their frequency and intensity, are selected during SLA development to meet these targets[3].

Performance targets cannot be easily quantitatively specified or calculated; rather, ongoing analysis activities at IAEA Headquarters are designed and tailored to the specifics of each State. In addition to these ongoing activities, additional activities relevant to these TOs (Complementary Access, environmental sampling, targeted analysis, trade an alysis , etc .) are determined based on the corresponding TOs priorities[4].

4. Identify Safeguards Measures and Activities: Safeguards measures and activities, that could be applied to meet each TO, are identified, based on the detectable indicators identified during the relevant acquisition step assessment, and taking the related SSFs into account[4].

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