Systems-Based Approach to Verification in Disarmament under the TPNW

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Abstract

The Treaty on the Prohibition of Nuclear Weapons (TPNW) offers nuclear-armed states two pathways for accession: disarm-and-join, where disarmament is completed before joining, and join-and-disarm, where disarmament occurs under a time-bound plan following accession. Although the join-and-disarm pathway enables immediate treaty adherence, it introduces significant challenges for verification, including ensuring irreversibility, safeguarding proliferation-sensitive information, and optimizing verification effectiveness. This study employs a systems-based approach to evaluate and compare this option in terms of verification strategies in different phases of disarmament process. Graph-theoretic modeling is utilized to map the network of potential rearmament routes, such as misuse of a reprocessing facility or diversion from dismantlement activities, whereas strategic game-theoretic analysis identifies optimal verification strategies and resource allocations to mitigate these risks. The comparative assessment highlights the conditions under which each pathway achieves maximum compliance credibility. By integrating a risk-based framework that prioritizes inspection resources toward the most attractive acquisition pathways, this research offers actionable insights for the design of robust verification protocols. These findings advance the objectives of the TPNW by enhancing the credibility and effectiveness of disarmament verification across diverse geopolitical contexts.

Introduction

The Treaty on the Prohibition of Nuclear Weapons (TPNW), which entered into force in 2021, represents a transformative effort to eliminate nuclear weapons globally. Unlike the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which also includes Nuclear Weapon States(NWSs) for which horizontal proliferation is prohibited, the TPNW has adopted a comprehensive approach. It bans nuclear weapons entirely, addressing their humanitarian and environmental consequences and providing pathways for nuclear-armed states to disarm (Article 4.2).

Among these provisions, the join-and-disarm pathway, which allows phased disarmament after accession, presents challenges for verification. Unlike disarm-and-join, in which verification occurs after complete disarmament, join-and-disarm requires continuous and dynamic monitoring. This raises critical issues, such as ensuring irreversibility, protecting sensitive information, and efficiently allocating verification resources [1,2]. Existing mechanisms, such as the International Atomic Energy Agency (IAEA) safeguards, are not fully equipped to address these demands [3,4].

The State-Level Concept (SLC), developed by the IAEA, enhances nuclear safeguards by shifting from facility-specific evaluations to comprehensive state-level assessments. A key component of the SLC methodology is Acquisition Path Analysis (APA), which identifies and evaluates the potential pathways that a state could use to reconstitute nuclear weapons [5,6]. However, current implementations focus on static proliferation risks rather than evolving threats during disarmament.

This study extends the APA methodology within a systems-based framework to optimize inspection resource allocation across different disarmament phases. It examines state strategies in post-disarmament contexts, assessing both the technical feasibility of reconstitution and effectiveness of verification strategies.

Methodology

In this study, a systems-based framework was developed for acquisition path analysis to verify nuclear disarmament. Inspired by the Tool for

Acquisition Path Analysis and Strategy (TAPAS) [7], developed under the German Member State Support Program, this framework was adapted for disarmament-specific scenarios, including pathways related to weaponization, dismantlement, and nuclear material disposition.

The framework begins with network modeling to represent state-specific nuclear infrastructure and material flows. Using IAEA's physical model, a state-specific acquisition model is constructed as a graph, where nodes represent material forms, and edges represent processes. Each process can be evaluated based on Technical Difficulty (TD), Proliferation Time (PT), and Proliferation Cost (PC), following the GIF PR/PP proliferation resistance measures [8].

Network analysis assesses the feasibility and risk of each pathway using metrics such as technical difficulty, proliferation time, and cost. A depth-first search algorithm extracts all plausible acquisition paths, with attractiveness calculated as the sum of edge weights, to enable systematic risk ranking. This step was automated using Python's NetworkX library to ensure transparency and reproducibility [9].

The final stage uses game theory to model the strategic interactions between the state and the inspectorate as two players. Each strategy combination corresponds to specific utilities for the players, forming a bi-matrix representation of the game [10]. Game theory then determines a solution using Nash equilibrium, where neither player can unilaterally change their strategy to improve their utility. This framework allows for the evaluation and comparison of different acquisition path configurations, with the effectiveness of an inspection regime measured by the inspectorate's payoff. Strategies include various inspection measures, each of which is associated with costs and detection probabilities. Given a cost threshold, the model computes minimum effort strategies to incentivize compliance. The justification for the game-theoretical approach and parameter selection is detailed in [11].

Key challenges include calibrating metrics to diverse state conditions and integrating expert judgments while maintaining objectivity. Iterative refinements and modular designs enhance the adaptability and reliability.

Results

An analysis of disarmament phases was conducted for a hypothetical nuclear weapons state with an advanced fuel cycle spanning both the civilian and military sectors. Under the TPNW's join-and-disarm option (Article 4.2), the state commits to a structured, verifiable, irreversible disarmament process. The process was divided into two phases: an elimination phase, where major disarmament actions occur, and a post-elimination phase, which ensures complete disarmament and prevents rearmament.

To examine the application of the modeled disarmament phases, a physical model was developed to simulate potential activities that a state might pursue during disarmament. These activities include diversion from dismantlement, misuse of shutdown facilities, unreported imports, processing in clandestine facilities, diversion from the civil fuel cycle, misuse of civil installations, and diversion from disposition.

The technical objectives focused on detecting and deterring prohibited activities, such as material diversion and facility misuse, along the plausible paths outlined in the model. The total expenditure for verification measures was estimated at €6,600,000[1] distributed across facility and activity types based on their respective risks. Expert assessments guided resource allocation by evaluating the attractiveness and cost implications of each diversion path.

The elimination phase involves dismantling nuclear warheads, shutting down weapon-related infrastructure, converting military reactors and reprocessing facilities for civilian use, and disposing of fissile material stockpiles. This phase is time bound and can be verified by a state-designated authority or the IAEA[2]. Figure 1

[1] An exemplary number is given for illustration purposes.

[2] To balance verification with security concerns, two approaches can be considered: transparent collaboration between the verification authority and the IAEA or a closed-segment approach, where all nuclear weapons, components, and weapon-usable fissile materials are confined within a monitored

highlights that during the elimination phase, diversion from dismantlement depots posed the most significant risk. The physical model identified 8,047 technically plausible acquisition paths, many of which were mitigated by targeted inspections and safeguards. This finding emphasizes the need for resource-intensive inspections at dismantlement sites to effectively reduce rearmament risks.

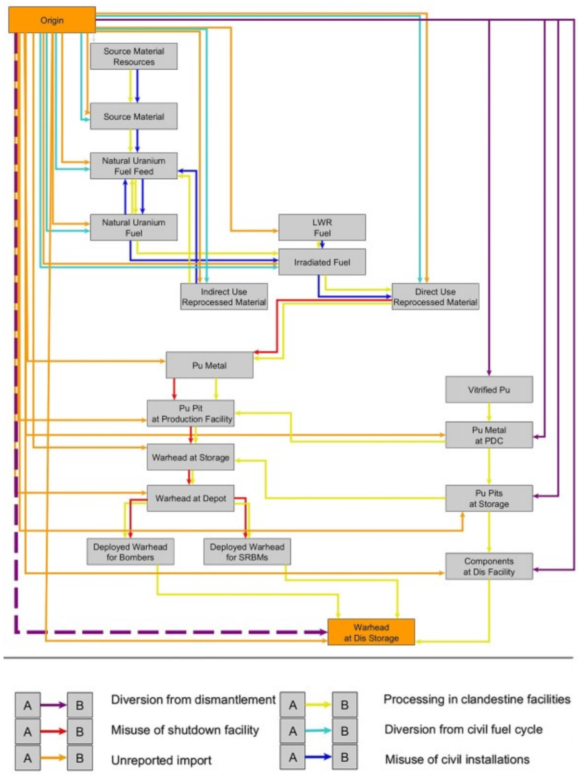

Figure 1: The Most attractive path for the state in elimination phase.

The post-elimination phase begins once disarmament is complete, transitioning the state into non-nuclear weapon status, with its nuclear materials and facilities under continued scrutiny. However, residual risks remain, particularly covert imports of weapons-grade materials. The analysis identified 205 acquisition paths, primarily involving undeclared imports, underscoring the need for stringent verification measures. The reduction in acquisition pathways from the elimination to the post-elimination phase reflects the effectiveness of inspections, which is further analyzed in Figure 2.

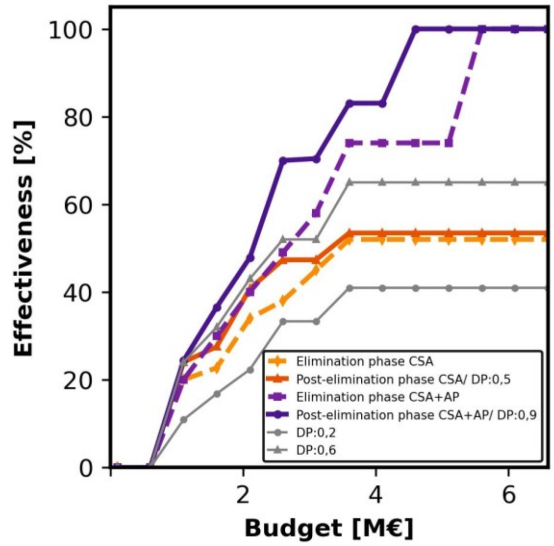

Figure 2: The inspection effectiveness depending on budget under CSA and CSA + AP for elimination and post-elimination phases.

The figure presents the results from an iterative model that evaluates how the inspectorate's budget influences inspection effectiveness in deterring non-compliance for different phases and safeguards implementations. We assume that safeguards are enforced from the outset of the disarmament process, with a Comprehensive Safeguards Agreement (CSA) or CSA supplemented by an Additional Protocol (AP) being implemented to ensure continuous verification [3]. If only CSA is implemented, safeguards will apply only to declared materials and facilities, thus limiting the ability to detect undeclared nuclear activities. Therefore, with an analogy approach [4], detection probabilities of clandestine facilities were assumed as 0.5 for

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segment of the nuclear complex. This approach enables oversight without granting direct access to sensitive information [2].

[3] Article 4.4 mandates that nuclear materials from disarmament be placed under IAEA safeguards "no later than the completion of the elimination process." Upon completing the elimination of its nuclear weapons and related programs, the state must conclude a CSA with the IAEA.

[4] The safeguards system assumes a 10% non-detection probability for both declared and undeclared activities when all verification measures (e.g., PIVs, IIVs, open-source analysis) are applied under CSA+AP. [12].

CSA and 0.9 for CSA+AP. The inclusion of AP significantly improves the ability of the inspectorate to deter illegal activities. This is evident from the 100% effectiveness in both the elimination and post-elimination phases under CSA + AP compared to CSA alone. The model developed for the post-elimination phase was also evaluated using different detection probabilities (0.2 and 0.6). The effectiveness metric is primarily influenced by the overall detection probability (DP) for a given inspection budget.

Conclusion

This paper presents a systems-based approach to verification in the context of nuclear disarmament under the Treaty on the Prohibition of Nuclear Weapons (TPNW), addressing the complex challenges inherent to the "join-and-disarm" pathway. By employing graph-theoretic modeling and game-theoretic analysis, the study identifies and evaluates potential acquisition paths while developing resource-optimized inspection strategies to enhance compliance credibility.

A key finding is the plateau effect in inspection effectiveness, which reveals a systemic constraint; no financial investment can compensate for incomplete legal access under CSA-only arrangements. This fundamental limitation affects the credibility of the join-and-disarm approach compared with alternative pathways, as verification remains contingent on pre-existing institutional commitments rather than purely technical solutions. Therefore, the TPNW does not explicitly require the adoption of the AP, it is strongly recommended to enhance verification and detect undeclared nuclear activities.

These findings offer actionable insights for policymakers and international agencies in designing credible and effective verification regimes.

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