Mapping Nuclear Verification

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ABSTRACT. Progress in nuclear arms control toward lower numbers of weapons will rely in part on the availability of viable treaty verification options that account for the entire life cycle of a weapon. The nature of these verification options depends on the direction that future reductions take (e.g. whether reductions emphasize warhead counting or fissile material balances) as well as the types of compromises that treaty negotiators are able to achieve in terms of balancing transparency and security. As researchers and policymakers work to make these verification options available, there is a significant need for a conceptual map to facilitate orientation and prioritization, and to help explain the context in which particular technologies are relevant. This paper presents a fictional state model – called "Nu" – as a tool to illustrate various verification strategies in terms of both options and needs. Nu has been built to host a nuclear fuel cycle and weapon life cycle that is representative of most states that possess nuclear weapons, including the elements of production, assembly, deployment, disassembly, and disposition. Also illustrated in Nu are possible pre-existing verification regimes, e.g. IAEA safeguards, New START measures, and CTBT measures. As a tool for achieving a birds-eye view, a primary use for the Nu model is to identify and help address potential diversion pathways for fissile material or weapons through verification technologies and approaches, with varying levels of intrusiveness and scope. Example approaches presented in the paper address future arms control treaty objectives, including a next incremental bilateral treaty between Russia and the United States, as well as a state joining the Treaty on the Prohibition of Nuclear Weapons. Each of the approaches offers strengths and weaknesses in terms of overall effectiveness, and each exhibits unique benefits and drawbacks from the perspectives of the hosts and inspectors. Readers should consider these approaches a starting point for discussion, as each can be broken down and recombined in numerous other configurations.

1. Background

With over 15,000 nuclear weapons still in existence in nine countries, nuclear arms control and disarmament efforts will rely in part on the availability of viable verification options that can be tailored to meet the needs of future treaty instruments. With the United States and Russia possessing the vast majority of these weapons, these needs may arise most immediately for nuclear arms control measures following the New Strategic Arms Reduction Treaty (New START), which remains in force until 2021 with the possibility of a five-year extension. Given New START's exclusive focus on strategic delivery systems (specified by range), follow-on measures will require new solutions to deal with non-deployed nuclear weapons, weapons awaiting dismantlement, non-strategic weapons and weapon-grade fissile material stockpiles.

Another pathway for reducing weapons toward their elimination lies in the newly adopted Treaty on the Prohibition of Nuclear Weapons. This treaty, while establishing a number of prohibitions related to nuclear weapon possession, allows for a state that has decided to disarm to join as a State Party and negotiate a protocol to ensure the verified and irreversible elimination of its nuclear weapon program. It further specifies that states parties to the treaty shall designate a competent international authority to conduct this verification. Given the comprehensive nature of such a process, challenges requiring new solutions will arise, particularly surrounding means to ensure that elimination is as transparent and irreversible as possible.

Other pathways for reductions and disarmament are also possible, including through multilateral agreements that may emerge between nuclear weapon-possessing states, or through unilateral decisions by individual states to disarm. Researchers are therefore tasked with developing a variety of options to meet the diversity of possible scenarios. This task includes optimizing individual technologies to maximize their simplicity and robustness and to minimize their intrusiveness, as well as building cohesive configurations of technologies and approaches that can cover the diverse set of facilities and objectives under any agreement.

2. Map and Website Overview

As researchers and policymakers work to make verification options available for the scenarios described above, there is a significant need for a conceptual map to facilitate orientation and prioritization, and to help explain the context in which particular technologies are relevant. Our research group has therefore created a fictional state model – called "Nu" – as a tool to develop and illustrate various verification strategies (available at: www.verification.nu). Nu has been built to host a nuclear fuel cycle and weapon life cycle that is representative of most states that possess nuclear weapons. As a tool for achieving a birds-eye view, the Nu model can be used to develop comprehensive verification solutions by identifying and addressing potential diversion pathways for weapons or fissile material through verification technologies and approaches, with varying levels of intrusiveness and scope.

The Nu mapping project is also integrated with a parallel project on virtual reality. While Nu allows for the development and assessment of verification approaches from a broad, strategic perspective, virtual environments allow researchers to dive a level deeper to further investigate technical, architectural and procedural details associated with each unique facility type. Researchers can examine verification approaches within an immersive virtual environment, allowing walk-throughs and person-to-person interaction, including the operation of equipment and the full simulation of virtual radiation fields and real-time detector response. Combining Nu and virtual reality can allow for substantial and flexible collaboration amongst research groups and governments working to find solutions to verification challenges.

The project website hosts a growing library of verification technologies under development in the research community. Verification technology innovation centers on answering challenges such as determining the accuracy of baseline declarations, authenticating a weapon without learning any classified information about it, and ensuring the absence of undeclared treaty-accountable items or facilities. The research community has made strides toward answers to these challenges, but more work and engagement are needed moving forward. The website will therefore exist as one available space to aid in organizing and coordinating complementary verification technology development efforts.

The facility set featured in the Nu state model contains the key facilities and elements associated with a nuclear weapon program, including the elements of production, assembly, deployment, disassembly, and disposition. The map layout remains flexible, allowing for the future incorporation of additional facilities relevant to nuclear weapon development, such as research facilities and those associated with important non-nuclear components of nuclear weapons. In its current state on the website, the Nu map provides an overview of key facilities and highlights some of the verification issues associated with each. These highlights are summarized in the following sections, which provide an overview of Nu's six regions.

Figure 1. The "Nu" Verification Landscape

For information on individual facilities, view the interactive version of the map at www.verification.nu.

Region 1: **Production** | The production region features the essential infrastructure for a nuclear fuel cycle. After uranium mining, conversion facilities deal with processing uranium ore concentrate to produce uranium hexafluoride (UF_6), a gas which will be able to undergo enrichment and which must be under safeguards. In recent years, the 'starting point' of International Atomic Energy Agency (IAEA) safeguards has been moved further back to include purified uranyl nitrate, an intermediate form of uranium used in the conversion process. Next, an enrichment facility processes uranium to increase the amount of uranium-235 in the material, with most modern enrichment plants using gas centrifuge to separate uranium isotopes. After material is fabricated into fuel and burned in a reactor, spent reactor fuel is chemically treated to extract plutonium and uranium, which can be reused as nuclear fuel or used in weapons. Safeguards at these facilities can be challenging, as nuclear material cannot be accounted for on an item-by-item basis (instead existing in bulk form), and inspectors cannot directly access material because of the its radioactivity.

Region 2: **Assembly |** At a nuclear warhead assembly facility, weapon-grade fissile material is manufactured into weapon components and combined with non-nuclear components. Access to assembly facilities will be most restrictive due to the exposure of classified design details. The intrusiveness of verification measures may depend heavily on whether a state is still actively producing or modernizing weapons. If production has ceased, verification might include more basic measures to verify shutdown. If production is active, verification would be more complex, with a boundary system serving as one possibility.

Region 3: **Deployment |** Deployment sites refer to military bases hosting nuclear warheads and their means of delivery, including bombers, submarines, and land-based missiles. The region also includes a number of smaller storage sites, referring to sites where warheads are stored in closed containers, conceivably at or near deployment sites and under military custody. While verification measures have been established for delivery systems, there are not yet measures for verifying warheads, which, in addition to being present on delivery systems, may also be present in nearby storage and maintenance facilities. Verification measures that attempt to account for warheads, in aggregate numbers and possibly with unique ID systems, may need to be able to account for the movement and maintenance of these items throughout and between storage and deployment sites. Perimeter or portal monitoring techniques could either focus on individual storage sites or on much larger deployment sites.

Region 4: **Dismantlement |** Warhead dismantlement facilities primarily deal with the separation of a weapon's fissile material components from non-nuclear components, including high-explosives, which can entail rigorous safety and access requirements. Disassembly can take place in multiple stages and over extended time periods, possibly requiring continuity-of-knowledge or chain-of-custody verification measures. Verification measures at dismantlement facilities may be complicated by the fact that several states have dual-purpose assembly and disassembly facilities.

Region 5: **Disposition |** A disposition or conversion facility is concerned with further processing fissile-material extracted from nuclear weapons. Disposition may involve rendering fissile material into an unusable form, through measures such as permanent storage or vitrification. This may also include downblending HEU to LEU and more drastic measures such as irreversibly changing the shape of weapon components (for example, "pit squashing"). Verification challenges may include how to conceal per-item mass and isotopics while maintaining adequate accountancy or continuity-of-knowledge.

Region 6: Hinterland | The Hinterland represents any area in a state with the potential to host undeclared fissile material, nuclear weapon components or nuclear weapons. Verification measures should in part be designed to prevent the diversion of items to the Hinterland or the illicit production of items in the Hinterland. Verification to prevent diversion can include chain-of-knowledge, accountancy, boundary or provenance measures. Detection measures could include challenge inspections or remote sensing. In general, verification measures should also include means to detect undeclared sites and activities that may exist independently from the declared infrastructures; this could include, in particular, satellite imagery or wide-area environmental monitoring or sampling.

3. Example Approaches

This section details two examples of how Nu can be used to assemble a verification approach for a given set of treaty objectives. The first example focuses on a hypothetical follow-on arms control treaty to New START concerned with warhead limits. The second example presents a hypothetical case of a nuclear-weapon-possessing state joining the Treaty on the Prohibition of Nuclear Weapons and eliminating its nuclear weapon program.

The distinct objectives of each type of agreement influence the nature of verification measures. Verifying reductions or limits on warheads will be more easily reversible given that the infrastructure needed to rebuild the arsenal would likely remain intact to support the maintenance of the remaining force. Verification of reductions or limits also faces the challenge of longevity and durability, given that any verification measures in the deployment, disassembly and disposition regions would need to be maintained over a long period to retain confidence in compliance. Any "breaks" between successive arms-control agreements would introduce uncertainties about compliance; an example of this is the Intermediate Range Nuclear Forces (INF) Treaty, where in the absence of the now extinct verification system, uncertainties about compliance have emerged. Finally, verification of reductions or limits poses the challenge of greater secrecy that is likely to be desired by parties to an agreement. Given that some nuclear weapons are understood to remain deployed, parties will therefore likely want to avoid giving an adversary too much information about deployment patterns, and verification measures would need to take this into account.

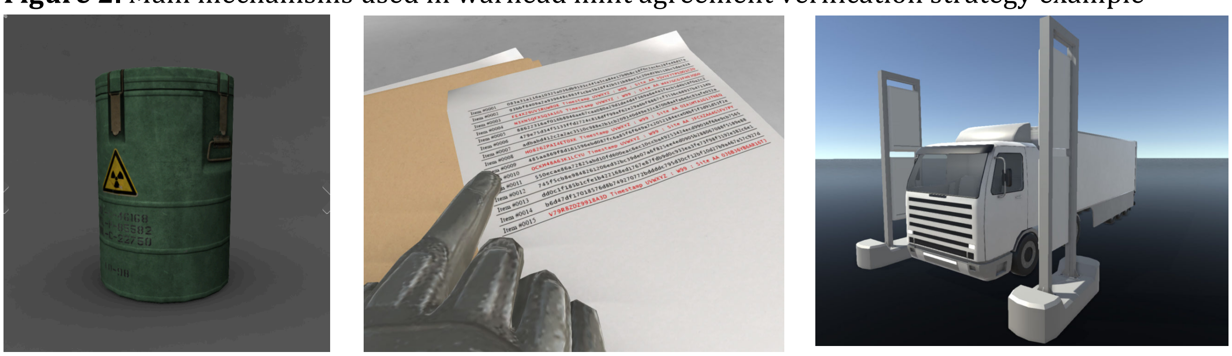
Alternatively, verifying the elimination of a nuclear weapon program may be more straightforward. In particular, the choice to eliminate a nuclear weapon implies a lesser need for secrecy surrounding deployment patterns. In this context, warheads might be able to be uniquely identified to provide greater confidence that they have been eliminated. Elimination is also distinct in that it may initially involve inspections at a wider array of facilities, including those associated with production and maintenance. However, if the reductions are part of a sustained move toward elimination, most of these measures would be temporary, with any enduring verification measures building on the International Atomic Energy Agency safeguards system, including measures included in a comprehensive safeguards agreement and additional protocol.

Each strategy below offers particular strengths and weaknesses in terms of overall effectiveness, and each exhibits unique benefits and drawbacks from the perspectives of the hosts and inspectors. Readers should consider these strategies starting points for discussion and further development, as each can be expanded, broken down or recombined in numerous other configurations depending on the priorities and available resources in each case.

Example 1: Warhead Limit Agreement | A follow-on agreement to New START could include an incremental reduction to U.S. and Russian nuclear forces consisting of limits on warheads. The Obama administration proposed in 2013 that a next bilateral agreement could include a reduction of about one-third of each country's arsenal, including reductions to non-strategic nuclear weapons. New START's verification regime focuses only on the verified conversion or elimination of strategic delivery systems (i.e. missiles and bombers), and does not deal with verification at the warhead level. A follow-on treaty would therefore face new verification challenges, including how to verify the elimination of individual warheads, non-deployed delivery vehicles, and non-strategic weapons.

The verification tasks inherent in an agreement of this nature would include, among others, assessing baseline declarations of non-deployed warheads and accounting and monitoring the fissile material components extracted from them. While there are numerous ways to approach these tasks, the basic challenge lies in balancing the needs to achieve inspector confidence while minimizing intrusiveness. The base set of mechanisms for this example verification approach includes an extension of the New START non-repeating identifier system to warheads,[1] hashed declarations for assessing baseline declarations and a portal monitoring system for monitoring extracted fissile material components (Figures 2 and 3).

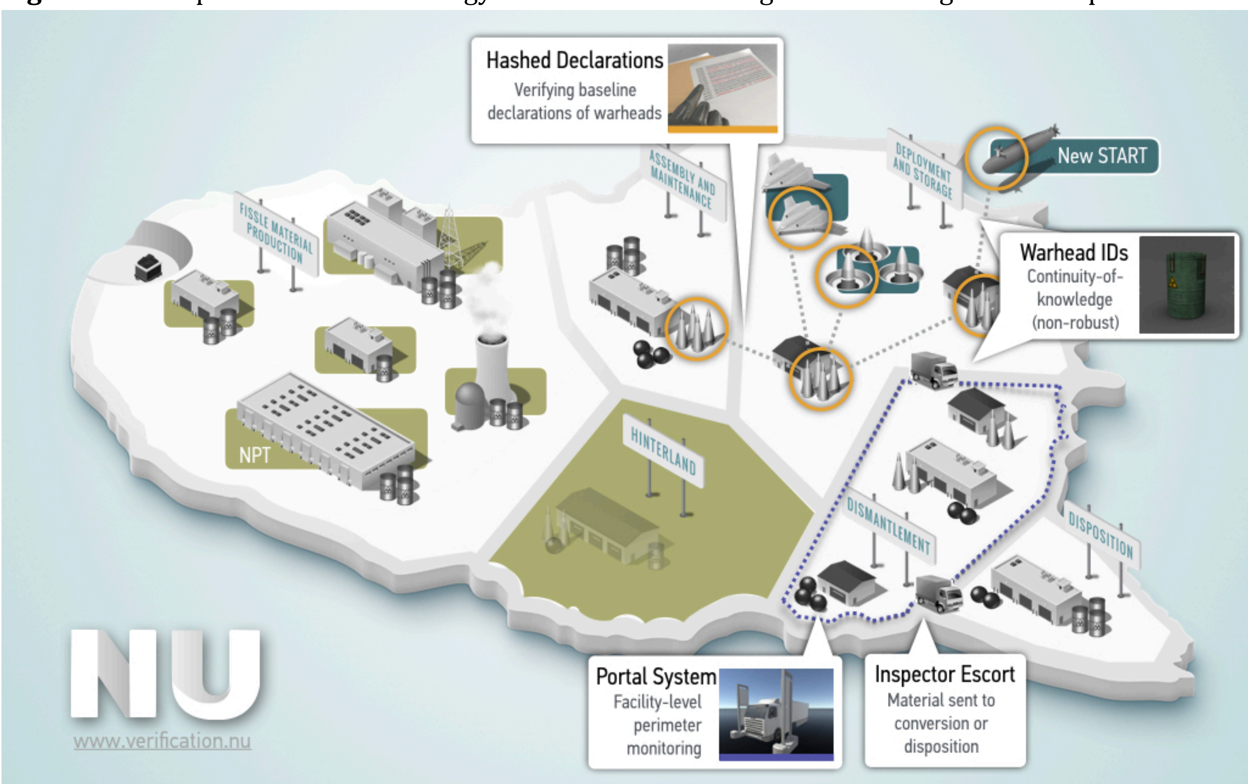
Figure 2. Main mechanisms used in warhead limit agreement verification strategy example



From left to right: Non-robust warhead ID system, hashed declarations for baseline warhead declarations, and portal monitor for perimeter control system. Images: From mariuse via Turbosquid (left) and from Princeton Nuclear Futures Lab (center and right).

To support the counting of warhead totals, this example verification strategy considers an extension of the identifier (ID) system for delivery vehicles under New START to warheads. New START defines an ID as a non-repeating alphanumeric number that has been applied by the inspected party to the first stage of a ballistic missile or to a heavy bomber and to the outside of any associated canister used to maintain, store or transport the missile. Additionally, the same ID is replicated directly on or near launchers in a place accessible to inspectors. The agreement does not call for any tamper-prevention measures and allows the state to determine the exact size of the ID.[2] Under a warhead limit agreement, this system might be extended to warheads. This could involve applying an ID to both a warhead and its associated container. As in the New START process, the host country would then track and report this ID as required as the warhead moves throughout the country. This process could be limited to tracking the ID and warhead at the level of bases, storage sites or facilities. Under an inspection protocol and within certain constraints (some of which are detailed in the following sections) inspectors could be allowed to read the IDs at sites associated with non-deployed warheads during inspections. Given the unlikelihood that inspectors would be able to read an ID on a warhead if it is deployed and on a delivery vehicle, inspectors could simply be allowed to view a list of the IDs of warheads that are deployed at a base under inspection.

Figure 3. Example verification strategy for a warhead limit agreement using the Nu Map



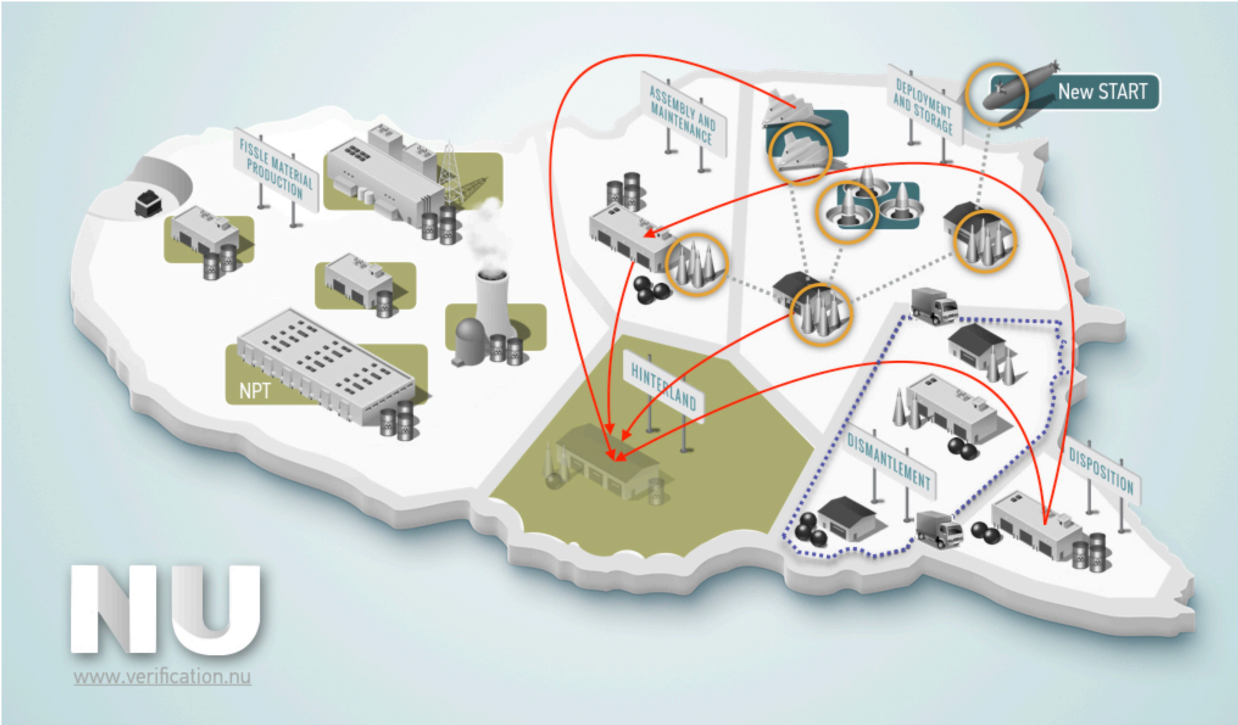
This example strategy utilizes a non-robust warhead ID system for accounting in the deployment and disassembly regions, hashed declarations for baseline warhead declarations in the deployment region, and a perimeter control system for securing the disassembly process.

Procedures and techniques to confirm upper limits on the number of nuclear warheads without revealing sensitive information about deployment patterns may be seen as an important verification task as warheads are further reduced. One mechanism for facilitating this objective is through hashed declarations, which are privacy-preserving declarations that might be usefully combined with the ID system for warheads. Hashed declarations would not list the locations (or other relevant data) of treaty-accountable items in cleartext. Instead, only, a hash (or "message digest") of each entry would be made public. Such a hash is much shorter than the original message itself, but the underlying cryptographic hash function is designed such that it is extremely difficult to find a valid message for a given hash or to construct two different messages that produce the same hash.[3] In preparation for an onsite inspection, the inspecting party would announce the storage or deployment location that it would like to inspect, and the host party would then provide the cleartext for all treaty-accountable items that are present at the selected site. This cleartext could include the IDs for warheads present at the given site. Especially if conducted on short-notice and over several iterations, these inspections can build confidence that the host state is reporting an accurate number of weapons.

Confidence in any agreed reductions could be supported by a perimeter control and portal-monitoring process, which would monitor vehicles and containers entering the complex. Such screening could be based on one or several sensors, for example radiographic imaging to obtain the shape of objects, or radiation measurement devices to detect the presence of nuclear materials such as uranium or plutonium.[4] New START provides neutron-count criteria for determining that an object is not a nuclear weapon, the inverse of which could provide an initial measure for identifying warheads entering a portal.[5] As weapons enter this perimeter-controlled complex, their IDs would be recorded. After this point, disassembly of the weapons could take place without an inspector present as long as the fissile material components remain in the perimeter-controlled area. Upon disassembly, the IDs should be transferred to the container of the associated fissile material components. Either periodically or at a later point in the agreement's timeline, the inspection team could perform an inspection to review and account for the extracted weapon components and fissile material. These items could conceivably be escorted by inspectors or tracked with other technologies to a separate conversion or disposition site, where inspectors could directly measure the material once it reaches an unclassified form.

While the strategy described provides assurance beyond what is offered in New START for verifying warhead limits and reductions, there are still numerous gaps that should be recognized and which can be illustrated using Nu (Figure 4). These include diverting fissile material extracted from weapons either back into new weapon production or to an undeclared site. Additionally, given that IDs are not linked to warheads in physically unique ways, there remains the risk that warheads could be diverted from the production or deployment regions and replaced by other items bearing the same ID as long as robust unique identifiers (UID) can't be demonstrated and fielded for this purpose. The system is also weakened by the uncertainty that warheads being counted and disassembled are real. Additional technologies (including those dedicated to warhead confirmation), approaches or inspection types could be designed and added to deal with these remain challenges as needed.

Figure 4. Remaining diversion pathways for warhead limit agreement verification strategy



The example verification strategy has a number of remaining diversion pathways and ways to reconstitute weapons. Additional technologies or approaches would need to be incorporated to close these gaps.

Example 2: Weapon Elimination Agreement | This next example presents a verification approach for the hypothetical case of a state eliminating its nuclear weapon program, for example, as part of joining the Treaty on the Prohibition of Nuclear Weapons. The strategy exhibits a number of variations from the previous example, including by establishing continuity-of-knowledge on individual items rather than using a perimeter monitoring system. Given that the objective of this agreement would be complete and irreversible elimination of a nuclear arsenal, there is less of a need for measures to protect sensitive information related to deployment patterns and weapon movements. This approach therefore aims to offer greater certainty that warheads, having been tracked from their delivery systems to the point of converting or disposing of the extracted fissile material, are indeed irreversibly dismantled. The base set of technologies for this example verification approach include buddy tags for assessing baseline declarations, a passive inspection system with information barrier experimental for confirming the authenticity of warheads, and a modal testing system for maintaining continuity-of-knowledge on an item (Figure 5).

For the task of assessing baseline declarations, this strategy employs buddy tags, which could be used at both deployed and non-deployed weapon sites. Given that attaching unique identifiers directly to warheads could be problematic due to a range of concerns by the host related to safety, security, and intrusiveness, buddy tags function as tokens that are physically separate from the treaty-accountable item.[6] The host must be able to produce one tag for each item without delay, and verification would therefore rely on short notice inspections. Sensors in the tag would show that it had not been moved to the inspected site after the inspection was declared (for example, within the last 24–48 hours). These tags can be used at both deployed warhead sites and non-deployed warhead sites given the requirement that they only need to be within the same complex as the associated weapon, and could in fact be in a completely separate building.

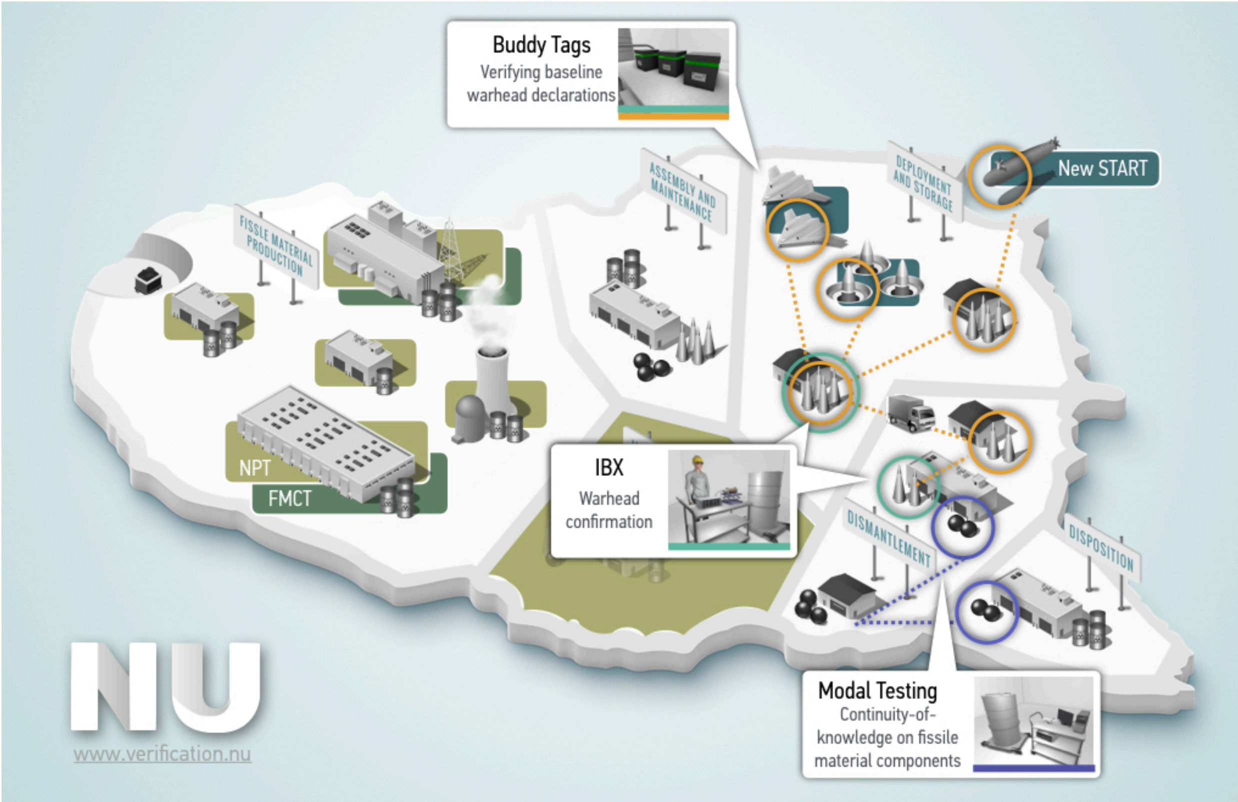
Figure 5. Main technologies in the weapon elimination agreement example verification strategy

From left to right: Buddy tags for baseline warhead declarations, information barrier for warhead confirmation, modal testing for chain-of-knowledge. Images from Princeton Nuclear Futures Lab.

Buddy tag inspections would ideally be supported by a warhead confirmation technology to help ensure that the tags are associated with real weapons. For the task of confirming warheads, this strategy employs a passive warhead confirmation system based on gamma spectrometry and an information barrier using a template-matching approach.[7] Template-matching first entails recording a radiation signature from a warhead trusted to be genuine. The signature of an inspected item is then compared against the reference signature, and depending on the agreement of the two signatures, the pass or fail signal appears. At a warhead storage site, the inspection team can randomly select a container to perform a confirmation measurement using the inspection system.

The example strategy also envisions that the inspection system with the information barrier would be used for warheads just prior to disassembly. After confirmation, inspectors would then need to remain nearby a secured dismantlement area until disassembly is complete in order to maintain continuity-of-knowledge on the extracted fissile material component (e.g. "pit"). After disassembly, continuity-of-knowledge on the extracted fissile material components could be achieved through uniquely identifying pit-container combinations through the use of modal testing. Modal testing is a specialized form of resonant vibration analysis often used for the purpose of structural identification, condition monitoring, and damage detection. It has been postulated that a modal vibration signature might be used to identify a particular treaty-accountable container or item-container system, or provide evidence of tampering.[8] A modal testing signature would therefore be acquired by the inspection team immediately following the warhead disassembly process. The container could then be placed in interim storage and would not need to be examined by inspectors again (through a second modal testing measurement) until just prior to conversion or disposition.

Figure 6. Example verification strategy for an elimination agreement using the Nu Map



This example strategy utilizes buddy tags in the deployment region for baseline warhead declarations, confirmation measurements in the deployment region and just prior to disassembly with an information barrier (IBX), and a modal testing measurement immediately following disassembly to maintain continuity-of-knowledge on the extracted fissile components until the point of conversion or disposition.

Overall, this strategy provides a higher level of confidence that items originating from delivery systems are converted or disposed of due in particular to the use of a warhead confirmation mechanism in both the deployment region and dismantlement region. However, it is a resource-intensive strategy that would require a significant level of inspector presence throughout the process. This might be mitigated by adding additional technologies or monitoring approaches to the strategy to reduce the load on inspections. In particular, inspector load might be significantly reduced if solutions are developed to ensure continuity-of-knowledge from a confirmed warhead to its containerized fissile material components. Given that warhead disassembly can be a lengthy process, technical or procedural solutions at this particular juncture would be beneficial.

4. Outlook

As researchers work to develop technical and policy solutions to future arms control and disarmament challenges, it remains important to increase understanding of the relationships between existing and possible future treaties, and to explore the potential synergisms of different verification technologies and approaches. The examples shown here illustrate how Nu can be used to assemble and evaluate a verification approach that considers the wider landscape of a country's infrastructure, and how it can illuminate remaining gaps and challenges toward the improvement of the given strategy. Future research using Nu would seek to build additional strategy options using different combinations of verification technologies and approaches, including both those described here and additional tools featured on the growing library of technologies on the Nu website. In close coordination with our team's work on virtual reality, future efforts will also be geared toward refining an evaluation framework to aid in understanding the relative strengths and deficiencies of different verification strategies at both broad and detailed facility levels, with the goal of generating viable option sets for future arms control and disarmament agreements.

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[1] Under START and New START, identifiers are called "unique identifiers" (UID), but these identifiers are host supplied and host applied. As Jim Fuller noted, the START "end-game under Bush I Administration resulted in inspecting party high-technology tagging being sacrificed," Jim Fuller, *US START TID Development Program: The Quest for Extreme Security Unique Identifiers (1986–1992),* April 2006, www.inmm.org.

[2] See provisions on unique identifiers in New Strategic Arms Treaty, Protocol and Annex on Inspection Activities. Available at www.state.gov/t/avc/newstart/c44126.htm.

[3] Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities, National Academy of Sciences, Washington, DC, 2005; Alexander Glaser and Sébastien Philippe, "Hashed Declarations of Nuclear Warhead Inventories for Early Commitment and Non-intrusive Verification," *58th Annual INMM Meeting,* Indian Wells, California, July 2017.

[4] J. P. Harahan, *On-Site Inspections Under the INF Treaty: A History of the On-Site Inspection Agency and INF Treaty Implementation, 1988–1991,* On-Site Inspection Agency, Washington, DC, 1993; D. Murer et al., "FLASH Portals: Radiation Portal Monitor SNM Detection using Time Correlation Techniques," *54th Annual INMM Meeting,* July 2013.

[5] Defining a nuclear weapon is a complex task and is explored further in Alexander Glaser, "Ceci N'est Pas une Bombe: Toward a Verifiable Definition of a Nuclear Weapon," *58th INMM Annual Meeting,* Indian Wells, California, July 2017.

[6] Sabina E. Jordan, Buddy Tag's Motion Sensing and Analysis Subsystem, Sandia National Laboratory, Albuquerque, New Mexico, 1991; S. DeLand, A. Glaser, J. K. Brotz, A. Kim, D. Steingart, and B. Reimold, Minimally Intrusive Verification of Deep Nuclear Warhead Reductions: A Fresh Look at the Buddy-Tag Concept, *57th Annual INMM Meeting,* Atlanta, Georgia, July 2016.

[7] J. Yan, A. Glaser, Nuclear Warhead Verification: A Review of Attribute and Template Systems, Science & Global Security, 23 (3), 2015, scienceandglobalsecurity.org/archive/sgs23jieyan.pdf.

[8] This preliminary work has mainly been conducted by the UK Atomic Weapons Establishment (AWE). See Helen White, Philip Daborn, Paula Hayden & Philip Ind, "The Use of Modal Testing within Nuclear Weapon Dismantlement Verification," *Science & Global Security,* 22 (2), 2014.