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Building up Transparency and Verification

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A Sandia researcher demonstrates new radiation detection equipment for New START treaty monitoring.

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2. Monitoring Regimes for All-Warhead Agreements

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ABSTRACT. *Arms control agreements between the United States and Russia negotiated after the end of the Cold War have imposed limits on the number of deployed strategic nuclear weapons. It is widely believed that future arms control agreements, either bilateral or multilateral, would place limits on all weapons in the stockpiles, including those in storage or slated for dismantlement, so that the gap between existing weapons and those captured by arms control regimes can be closed. Verification of such "all-warhead" agreements is likely to face some fundamentally new and complex verification challenges. This chapter examines three types of monitoring regimes that could be used to verify such agreements: the absence regime, the limited-access regime, and the confirmation regime. These regimes can build on each other, and they can be gradually phased in. While research and development on advanced verification technologies continues, all-warhead agreements could initially be verified using absence or limited-access regimes, where technology gaps are small.*

Introduction

Arms control agreements between the United States and Russia negotiated after the end of the Cold War have imposed limits on the number of deployed strategic nuclear weapons. It is widely believed that future arms control agreements, either bilateral or multilateral, would place limits on all weapons in the stockpiles, including those in storage or slated for dismantlement, so that the gap between existing weapons and those captured by arms control regimes can be closed.[1] Verification of such "all-warhead" agreements are likely to face some fundamentally new and complex challenges and may require new verification technologies and approaches to nuclear inspections.

This chapter proposes and examines three different monitoring regimes that could be used to verify nuclear disarmament. This discussion is preceded by a brief review of technologies and approaches that are most relevant for these efforts.

The verification regimes discussed here are all based on the premise that the parties make declarations as part of the agreement. These would typically include baseline declarations made at the outset followed by regular updates, data exchanges, and notifications.[2] Fundamentally, such a framework is aimed at confirming treaty compliance at declared sites and, as always, there remains the possibility that undeclared items exist at undeclared sites. While onsite inspection regimes may also provide some confidence in the absence of undeclared sites, other monitoring approaches may have to be used to adequately address this concern. These approaches are not part of the discussion below but are addressed elsewhere in this report.

What are the main non-compliance scenarios that can be addressed with onsite inspections conducted as part of a disarmament verification regime? A major objective is to deter and detect non-compliance at declared sites where verification activities take place. This can include the presence of undeclared items "hidden in plain sight" but – as we will see – this strategy is risky for a non-compliant state even for the most basic verification regime. The more robust a regime with onsite inspections becomes, the more likely a non-compliant party would have to consider undeclared sites for prohibited activities including, for example, storage of undeclared items. Ideally, any regime should therefore also allow challenge inspections elsewhere. One of the most stringent inspection regimes would be one that includes the verified dismantlement of nuclear weapons. This is introduced as the confirmation regime below. It is important to recognize, however, that such a regime only becomes relevant and worthwhile as part of a comprehensive verification framework that tracks nuclear warheads from deployment through dismantlement and has strong provisions in place to also address concerns about potential undeclared sites. Warhead dismantlement verification is not particularly meaningful when other aspects of the weapons complex remain shrouded in secrecy. As such, it is natural to consider simple, non-intrusive verification regimes first and to phase-in additional elements over time as the parties seek additional confidence in the correctness and completeness of declared warhead inventories.

Technologies and Approaches

Verification of nuclear arms control agreements can benefit from decades of experience with nuclear safeguards, primarily developed to support the work of the International Atomic Energy Agency.[3] Nuclear safeguards are applied to nuclear materials in the civilian nuclear fuel cycle; in contrast, nuclear arms control inspections are typically conducted at military sites and deal with sensitive items. Unsurprisingly, some verification technologies and concepts can be directly adopted from the safeguards world; for others, however, there is no relevant prior experience. These are often the areas where the most significant technology gaps exist and where no clear consensus on adequate verification approaches has so far been reached.

Unique identifiers (tags) and seals

Tags and seals are a workhorse of the IAEA safeguards system, and they have also been used for arms control verification purposes. As part of a monitoring regime, tags and seals are often used in conjunction, but they generally serve different purposes. A tag is “a device, or an applied or intrinsic feature, used to uniquely identify an object or container.”[4] Simple tags (such as serial numbers) can serve as inventory devices when no adversary is present. Tags used for verification purposes are typically “security tags” that have tamper-indicating features and are difficult to replicate or counterfeit. A seal is “a tamper-indicating device designed to leave non-erasable, unambiguous evidence of unauthorized access or entry."[5] Unlike locks, seals are not necessarily meant to prevent or resist access; they only record that access has taken place since the seal was applied.

The costs of a tag or seal can be anywhere between a few cents and thousands of dollars per unit. Regardless, every tag or seal can be defeated given the relevant expertise and with sufficient time and resources.[6] In general, the choice for the "right" type of tag or seal depends on the particular use case. For example, a low-cost seal offering medium security may be considered appropriate when used for hundreds of containers with small quantities of low-interest material. In a nuclear-warhead monitoring regime, however, much higher security standards are likely to apply.

While overall receiving relatively attention as part of international R&D efforts, some experts have warned about the vulnerabilities of tags and seals and have produced extensive lists of possible attack strategies.[7] In this context, defeating a seal often means opening and resealing the seal, presumably after having tampered with the content of the container; defeating a tag often means lifting the tag and applying it to another item or container. It may be possible to successfully duplicate tags or seals, either by replication or counterfeiting, in which case both become useless. Sabotage, often using standard misdirection techniques,[8] is another important class of attack. Typically, sabotage is most effective during application or readout of the tag or seal.[9] More generally, an adversary can also seek to sabotage the entire process, for example by deliberately designing hidden vulnerabilities into a tag or seal technology. These backdoor and many other types of attacks on tags and seals require direct access to the items (containers) that are being monitored. One important strategy to prevent such attacks is to monitor the tag or seal itself, for example, using surveillance cameras;[10] in this case, the adversary needs to compromise two distinct technologies at the same time. Tags and seals will play an important role in two of the three monitoring scenarios examined below. While research and development on tags and seals continues, future nuclear arms control applications could benefit significantly from state-of-the-art technologies using, for example, concepts from modern cryptography for electronic tags and recent advances in using physically unclonable functions for security applications.

Chain of custody technologies

In nuclear safeguards and verification, chain of custody is "the process whereby measures are taken to ensure that an accountable item is not substituted or diverted while held under control."[11] The terms "chain of custody" and "continuity of knowledge" are sometimes used interchangeably; more precisely, however, chain of custody is a *process* whereas continuity of knowledge is an *outcome*.[12] In general, when an item enters a monitoring regime with a confirmation measurement ("initialization") and chain-of-custody methods are effectively applied, continuity of knowledge can be established and maintained, and additional confirmation measurements may not be deemed necessary. The objective is to sustain continuity of knowledge over longer periods of time, as the sealed item may be handled by the host and move from one site to another, while inspectors are not present at the site. In practice, interruptions in the continuity of knowledge will occasionally occur, in which case the baseline knowledge needs to be reestablished to reconstruct the missing information.

In addition to tags and seals, discussed in the previous section, prominent chain-of-custody technologies include tamper-indicating enclosures and surveillance equipment. Portal monitors can also be deployed and used as a chain of custody technology.

Tamper-indicating enclosures. Seals serve as tamper-indicating devices, but they cannot preclude the possibility that an adversary bypasses the seal altogether, for example, by cutting or drilling through the side of a container while its sealed lid remains intact. A tamper-indicating enclosure (TIE) seeks to address this scenario by providing the means to ensure the integrity of a physical space or volume. Tamper-indicating enclosures can serve as bodies for equipment, as enclosures for monitored items, or as entire rooms, in which items are stored.[13] Ideally, enclosures used as part of a monitoring regime are specially designed to maximize robustness against tampering; as one such example, the enclosure of a radiation measurement system is shown below. Similarly, the interior of an enclosure can be continuously monitored for illicit access using a variety of phenomena and sensors. There are many use cases of tamper-indicating enclosures in nuclear disarmament verification, most notably perhaps the possibility of storing warheads or other treaty-accountable items in containers that simultaneously serve as tamper-indicating enclosures. This is another area where additional research and development efforts are important and likely to make significant contributions.

Surveillance equipment. Surveillance has been traditionally based on optical systems.[14] It is most effective in storage areas where routine activities are infrequent and the amount of footage generated is small. The use of optical systems (cameras) in areas where sensitive items are handled is likely to be controversial and very limited at best. Since the 1990s, there have been efforts to develop systems based on sensors that can detect minute changes or movements in a storage room without relying on visual information. These include, for example, the Integrated Facility Monitoring System (IFMS) and the Magazine Transparency System (MTS), the latter using microscopic changes in the magnetic field to detect illicit movements of containers in a storage area.[15] In principle, numerous approaches for continuous remote monitoring based on a variety of sensors and technologies could be pursued. As with other technologies, establishing and maintaining trust in the sensors and the authenticity of the transmitted data (such as, for example, precluding replay attacks)[16] remains one of the main challenges.

Portal monitors. Portal monitors are widely used for security applications to detect radioactive materials passing through an entrance or exit. Portal monitors have also been proposed as a chain-of-custody technology to support nuclear arms control verification.[17] When deployed in pairs, one after another in a hallway, portal monitors could confirm not only the passage of a (radioactive) treaty-accountable item but also the direction of motion into and out of a designated area, which may not have any other exits. Used in such a configuration, portal monitors could therefore also play a relevant role in warhead dismantlement scenarios, in which inspector access to certain areas cannot be facilitated. The monitors could then guarantee that the material that entered a room has also left that same room.

Radiation detection equipment

All fissile materials are radioactive, and well-established technologies exist for detecting and characterizing plutonium and uranium, which are the key ingredients to make nuclear weapons. Measurement techniques can be passive or active, and they can seek detection of gamma or neutron radiation or both. Radiation detection equipment (RDE) is one of the main types of non-destructive analysis (NDA)[18] equipment and, given its unique role for verification applications, it is discussed separately here.

Gamma and neutron (gross) counting. The mere presence of radioactive material can be a relevant observation during an arms control inspection. Both uranium and plutonium emit gamma radiation (i.e., high-energy photons, typically, with energies in the 100–3000 keV range), which may be clearly detectable above the naturally occurring background.[19] A variety of very basic detectors exist to detect the presence and (total) intensity of gamma radiation, which includes for example the Geiger-Müller counter. Plutonium and some other actinides are also strong neutron emitters. The presence of neutrons is a more unique signature than the mere presence of (gamma) radiation, and it can in fact provide some confidence in the presence of a plutonium. Neutrons can be detected using gas-filled proportional counters, in which charged particle are produced following neutron capture. This reaction is most pronounced for very low (thermal) neutron energies, and neutron detectors therefore often include a medium to slow down fast neutrons to appropriate energies.[20]

Gamma spectroscopy. The energy of gamma radiation can be determined with several types of detectors. To this end, the energy of the photon is converted to an electrical charge, which is then collected and turned into a voltage pulse that scales with the energy of the original photon.[21] In the course of such a measurement, a gamma spectrum can be acquired, which can be used to identify specific elements or isotopes that are present in the inspected item. Depending on the detector type, it may also be possible to determine additional characteristics, such as the age of the material, based on the relative abundance of certain decay products. Gamma spectroscopy can also be used to generate a unique "fingerprint" of an inspected item, which may encode both the mass and the configuration of the item and therefore be used to confirm the type or identity of a treaty-accountable item.

Attribute and template measurements. Two fundamental concepts have been proposed to confirm that a treaty-accountable item such as a nuclear warhead is authentic: the attribute approach and the template (or template-matching) approach. The attribute approach examines a set of properties that are considered characteristic for nuclear weapons; this can include qualitative criteria, such as the mere presence of a special nuclear material (for example, the presence of plutonium), and quantitative criteria, such as meeting agreed threshold values for mass or isotopics (e.g. a maximum ^{240}Pu content). In contrast, the template approach does not seek to determine absolute or relative attributes of the inspected item; instead, it compares a unique radiation signature or "fingerprint" against a previously recorded template generated with a reference item that is known or believed to be authentic.

Both attribute and template systems face some additional challenges that are characteristic for each approach. In the case of attribute measurements, the question arises what types of attributes should be selected and what the exact threshold values for those attributes should be.[22] In general, the more representative the attributes (and, when applicable, their threshold values) are, the more robust the verification approach will be; but more information about the inspected warhead would necessarily be revealed also. In the case of template measurements, qualitatively different challenges exist; these include: how to establish the authenticity of the template in the first place, how to protect sensitive design information that the template contains, how to account for differences between valid items (e.g. manufacturing tolerances, age of material) and how to store the template between measurements so that the inspector remains confident in its authenticity.

Information barriers. The radiation signatures acquired with both the attribute and the template method are considered highly sensitive and cannot be revealed to an inspecting party seeking to confirm the authenticity of a nuclear warhead. Primarily for this reason, warhead inspections generally involve complex measurement techniques and procedures. To enable such measurements, the concept of the information barrier has been developed since the late 1980s.[23] An information barrier processes the acquired radiation signatures but displays the outcome of the analysis in a simple pass/fail manner. There are at least two critical functional requirements for the barrier: First, the inspected party must be assured that classified information is protected so that under any circumstances, i.e., even when the equipment is malfunctioning or operated incorrectly, only non-sensitive information is presented to the inspecting party ("certification"); second, the inspecting party must be confident that the inspection system measures, processes, and presents the conclusion drawn from the data in an accurate and reproducible manner ("authentication"). Simultaneously certifying and authenticating information barriers has been the most serious obstacle to demonstrating the concept as a viable verification technology.

Monitoring Regimes

We consider three different monitoring regimes: the absence regime, the limited-access regime, and the confirmation regime. This sequence of regimes is similar to the one proposed and discussed in Chen et al. (2016).[24] Verifying an "all-warhead" agreement could begin with an absence regime, which is relatively straightforward to implement and uses only technologies and approaches that are already being used. The limited-access regime could follow such a minimal regime to provide additional confidence in treaty compliance; it would introduce unique identifiers for all treaty-accountable items. Finally, the confirmation regime would further strengthen the monitoring regime by confirming the authenticity of declared items and by tracking them through the dismantlement process. Ideally, the recovered materials would be placed under safeguards or eliminated to ensure a degree of irreversibility of the process. Importantly, these three regimes build on each other and could be gradually phased in.

Virtually all verification regimes envision baseline declarations that all parties make at the outset. The purpose of subsequent inspections is to gain confidence in the correctness and completeness of these declarations and to ensure that changes to them (for example, reductions in the declared inventory due to warhead dismantlements) are legitimate. In the following, we assume that these declarations exist and that the parties have agreed to relevant data exchanges and notifications.

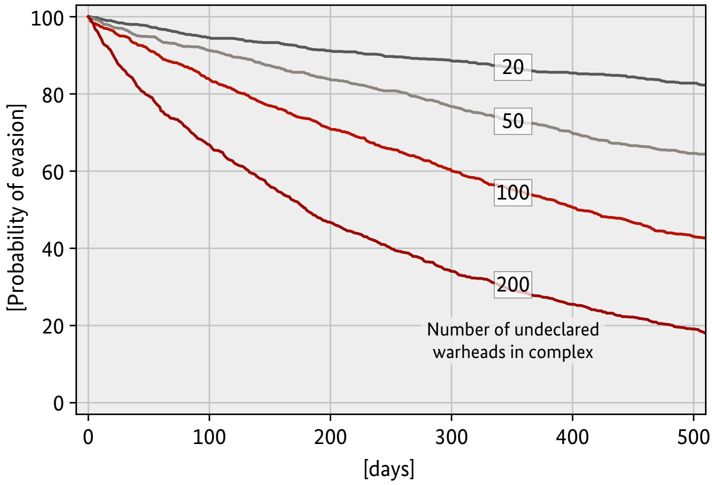
The absence regime: confirming numerical limits without access and identification

The most basic approach to confirming numerical limits as part of an "all-warhead agreement" is to rely solely on baseline declarations followed by regular data exchange. No tags are needed, and no treaty-accountable items are ever accessed or inspected. This is essentially the approach followed by New START for deployed strategic nuclear weapons, but it can in principle be expanded to non-deployed weapons. In this case, during an onsite inspection of a site selected by the inspector, which can either be a site that is declared to hold treaty-accountable items or not, the host gets "credit" for the number of items declared for that site and identifies those items as such. These declared items will be accepted as treaty-accountable items and never accessed or inspected.[25] The inspectors would then be allowed to confirm that other items available at the site are in fact not treaty accountable. During the negotiations of the underlying agreement, the parties could agree on certain physical characteristics of objects that qualify for further inspection, such as the minimum dimensions of a storage container. In many cases, the host may be able to simply provide visual access to items or containers that have been flagged by the inspector to demonstrate that the item is not treaty accountable; there may be cases, however, where this approach is not possible or practical. In these cases, the inspector could be allowed to make radiation measurements to confirm the “absence of a nuclear weapon” or, more specifically, to confirm that a container does not contain sufficient amounts of plutonium or uranium to make a nuclear weapon. In principle, this can be done with simple neutron or gamma (gross) count measurements.

Neutron measurements. Simple neutron detectors have been used for many years as part of New START to confirm that an object is “non-nuclear.”[26] Only plutonium, however, emits neutrons in significant quantities; uranium does not, and the technique can therefore not be used for uranium-only weapons or weapon components. Based on the experience with New START, the technology and its use for absence measurements can be considered mature.

Gamma measurements. Relying on the detection of gamma emissions, instead of or as a complement to neutron emissions, could simultaneously confirm the absence of both plutonium-based and uranium-based weapons, which may be relevant for other types of nuclear weapons or weapon components. Gamma radiation is more easily shielded than neutron radiation, however, which may require additional provisions in the inspection protocol; it still should be possible to confirm the absence of a threshold quantity of plutonium or uranium within minutes, even if a shielded container is inspected.[27] Such an instrument has not been used for arms control verification purposes to date, but the technology itself is straightforward and easily deployable in the field.

In a verification regime based on absence measurements, no weapons should ever be part of an inspection, and safety and security concerns would therefore be dramatically reduced. Information barriers, if needed at all, could be relatively simple.[28]



The odds of evading detection when hiding "in plain sight." In this notional scenario, 1000 warheads have been declared but additional, 20–200 undeclared warheads exist at declared locations in the weapons complex. Inspectors are allowed to conduct twelve short-notice onsite inspections per year. At any given time, about 200 warheads are deployed on submarines or mobile missile launchers and unavailable for inspection. In this particular scenario, 20 additional warheads would remain undetected within the first year with a probability of about 85%; the odds of finding a discrepancy over the same time period are about 50:50 when 100 undeclared warheads exist in the complex. The host is not pursuing any strategies to minimize the odds of detection other than minimizing the number of locations where discrepancies between the declared and the actual inventory exist; in particular, no attempt is made to preferably locate undeclared warheads on deployed platforms so that detection can be evaded. Authors' estimates based on a model inspired by the analysis in Chen et al. (2016). The chart is based on 1000 simulations of each scenario.

A pure absence regime would not involve any access to treaty-accountable items, for example, for identification purposes using unique identifiers (tags). Naturally, this opens up some ambiguities. In particular, for whatever reason, the host could be overdeclaring the inventory, i.e., have fewer weapons in their arsenal than declared (the same will be true for the identification regime discussed next). Both aspects can be considered advantageous for an initial monitoring regime that minimizes intrusiveness, while the parties may find some ambiguities about their own arsenals and operations preferable.

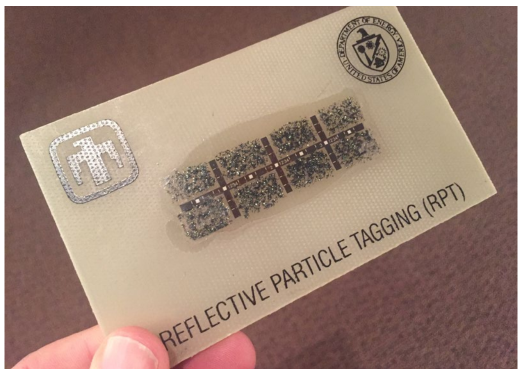
While overdeclaring the warhead inventory is not particularly problematic from the perspective of treaty compliance, underdeclaring the inventory clearly is a major concern. The question therefore arises how likely it is that undeclared treaty-accountable items can be hidden in plain sight – a scenario that will be relevant for almost any monitoring regime. Such a non-compliance strategy could be motivated by the finite number of routine or short-notice (challenge) inspections that the parties are allowed to conduct annually. It is reasonable to assume that such a strategy would not only involve a single or a few items; rather, one can assume that a certain minimum fraction of the declared arsenal would be undeclared. As the model and the figure above illustrates, even a modest number of onsite inspections would have a high and probably unacceptable chance of detecting discrepancies in the few-percent range within 12–24 months. Such simple models also highlight the importance of declarations that commit the parties to numbers that are facility or platform specific (say, the number of warheads held in a particular storage facility or deployed on a specific submarine) in order to make this non-compliance scenario as unappealing as possible. Concepts for privacy-preserving declarations have been proposed, which could address potential security concerns parties may have about revealing that information.[29]

The limited-access regime: confirming numerical limits with positive identification

An absence measurement regime avoids access to treaty-accountable items altogether. Inspection activities would be focused entirely on other objects that are present during an inspection of a declared or undeclared site, say, on storage containers that are large enough to accommodate a treaty-accountable item. This follow-up regime can build on this simple and least-intrusive regime, but it would add some elements of positive identification to it in order to gain additional confidence in the correctness of the declarations made by the other party.

In the most straightforward case, unique identifiers (tags) would be applied to all treaty-accountable items. Tagging treaty-accountable items with unique identifiers (UIDs) transforms a numerical limit into a ban on untagged items.[30] The identity of selected treaty-accountable items – but not their nature – could be confirmed during onsite inspections by confirming the integrity and the ID of the tag. Over time, the inspecting party would therefore develop an understanding of the movements of treaty-accountable items through the weapons complex of the other party. Based on these movements, the inspecting party would gain some confidence in the fact that the monitored item is in fact a nuclear weapon, i.e., the “provenance” of the item could gradually be established;[31] on the other hand, the host party may be concerned about revealing sensitive operational and other details (such as maintenance schedules), but some techniques may be available to mask some of the data. It may well be that a limited-access regime, a regime without confirmation measurements, could be considered fully adequate for deep cuts in the nuclear arsenals.

Tagging treaty-accountable items may pose some challenges but none of them should be insurmountable even with existing verification technologies and approaches. Warheads in storage are (or can be) containerized. These containers can then be tagged and sealed; ideally, containers could also serve as tamper-indicating enclosures to provide additional confidence in the integrity and nature of its content. The unique identifier of the container would then “represent” the warhead itself, whose serial number could be reported as well. Similarly, it should be possible to uniquely identify gravity bombs. As discussed above, a wide variety of tags and seals is available to accomplish this task, and the parties could choose from several options balancing security, cost, and complexity. Monitored storage of warheads or bombs could be complemented by additional containment and surveillance methods (including, remote monitoring) if desired. Some of the required procedures may be complex, but all relevant technologies are available.



On the left: Demonstration of the B61 nuclear weapon disarming procedures. On the right: The Reflective particle tag (RPT) is one of several unique identifiers that are considered extremely difficult to duplicate or otherwise compromise.[32] It was done using a “dummy” (inert training version) in an underground vault at Volkel Air Base in the Netherlands in June 2008. It is plausible to assume that an international inspector would be allowed to approach a gravity bomb close enough to read out a unique identifier. *Source: Author and United States Air Force.*

For deployed warheads on missiles, different approaches may have to be pursued. New START currently uses unique identifiers only for missiles (ICBMs, SLBMs) and heavy bombers; warheads are counted but not identified. Uniquely identifying a deployed warhead given access restrictions may be challenging. It may well be that the parties agree on a simplified method for these warheads, for example, by simply accepting serial numbers or other identifiers provided by the host. Even without verifying these numbers independently during inspections of deployed systems, inspectors may over time gain confidence in the correctness of these numbers based on overall consistency of the declarations over time. Occasionally, warheads may also appear in storage or during maintenance where their identity may be more easily confirmed.

Another approach supporting a limited-access regime could be the use of "Proximity Tags" or "Buddy Tags." First proposed in the late 1980s, this concept seeks to overcome concerns about safety and intrusiveness by separating the tag from the treaty-accountable item itself.[33] In a tagging regime using buddy tags, a party would declare a its inventory of treaty-accountable items and receive exactly one (unique and unclonable) tag for each. The monitored party would then co-locate these tags with the items. The basic idea is that, during a short-notice onsite inspection later on, the inspected party must be able to present one buddy tag for each treaty-accountable item present at the inspected site. This concept could be modified to support a limited-access regime.

The confirmation regime: warhead confirmation and verified dismantlement

At some point prior to dismantlement, and even if verification arrangements seeking to confirm numerical limits on nuclear warheads have been in place for extended periods of time, the inspecting party will prefer or require reassurance that declared warheads are authentic so that further reductions in the arsenals can be considered credible. Such a confirmation regime could build on the ones discussed earlier (i.e., the absence regime and the limited-access regime) but include actual measurements on nuclear weapons. It's the only regime where significant technology gaps continue to exist. Even though major research and development efforts have been underway for over the past thirty years, no inspection system has been successfully demonstrated in a true inspection setting, i.e., with measurements on actual nuclear weapons and the participation of international inspectors, while meeting the requirements for certification and authentication of instruments and data.

The confirmation regime envisions measurements to confirm the authenticity of declared nuclear weapons prior to dismantlement (using an attribute or template-matching approach) and perhaps also during the "life cycle" of randomly selected weapons. The confirmation regime provides the highest confidence in the correctness of declared inventories and reductions. Several types of inspection systems using a variety of radiation measurement techniques have been proposed for confirmation measurements. These measurements are generally highly intrusive, and authentication and certification of information barriers has so far proven difficult.

Note that a regime that includes verified dismantlement of nuclear weapons and places constraints on the fissile materials recovered from them, i.e., by applying safeguards on these materials or by verifying their elimination or disposition, would provide additional opportunities for inspectors to confirm the correctness and completeness of declarations. In particular, knowledge about the total amounts of fissile materials produced by a country could provide confidence in the fact that undeclared stockpiles of weapons do not exist. Historic production of plutonium and highly enriched uranium can be estimated using methods of nuclear archaeology.[34] These number could be reconciled as material from dismantled warheads is becoming available.

It is also worth pointing out that, over time, inspectors would be able to draw some conclusions about the average amounts of plutonium and uranium contained in dismantled weapons.[35] While the host party may generally be concerned about revealing this information, some early verification concepts were based on the assumption that the aggregate quantities and average isotopic composition of materials "contained in a mix of several different types of warheads can be declassified in the course of future treaty negotiations."[36] Such a concept could drastically simplify the verification of deep cuts as confirmation measurements may not be considered essential at all. This question has received relatively little attention as part of past and ongoing studies but deserves more attention.

Conclusion and Outlook

For thirty years, international research and development efforts have sought to develop inspection systems that can confirm the authenticity of a nuclear weapon to support the verification of future arms control treaties, which may include non-deployed weapons and verified dismantlements. With few exceptions, little progress has been made toward certifying and authenticating such candidate systems, primarily due of security concerns associated with such measurements involving highly sensitive items. In this chapter, we have examined a different approach.

Here, we consider three basic regimes for nuclear disarmament verification beginning with a simple regime that is straightforward to implement and only uses existing technologies and already established procedures. The other regimes can build on this foundation and be gradually phased in as technologies become available and treaty parties seek to strengthen the verification regime.

First, an absence measurement regime can provide a reasonable starting point for verifying all-warhead agreements. Here, we follow the proposition of simply accepting as weapons all "items declared as weapons" by the host. The technologies needed to support an absence regime are mature and already used for other arms control applications. In particular, Russia and the United States have been using neutron detectors for many years as part of New START inspections. In a verification regime based on absence measurements, no weapons should ever be part of an inspection, and safety and security concerns would therefore be dramatically reduced.

Second, a limited-access regime with positive identification of treaty-accountable items could be phased in over time. Serial numbers or unique identifiers would be used to identify declared items. Measurements on treaty-accountable items are still not envisioned at this stage, i.e., the authenticity of the warheads themselves is not confirmed. The only new technologies required to support a limited-access regime are tags and seals. Containment & surveillance technologies could also play a relevant role; in particular, declared warheads or warhead-components in long-term storage could be monitored remotely with minimum efforts and interference. Again, all technologies needed to implement such a verification regime are available today, and ongoing and future research could be focused on joint development of advanced tags and seals. It is likely that the access procedures required for this regime would be the more difficult part to negotiate, and international efforts could usefully focus on these aspects, in particular, how to apply and read-out unique identifiers on treaty-accountable items.

Third, a confirmation regime would finally require those instruments that have so far been elusive, i.e., radiation measurement systems with information barriers for attribute or template measurements. These systems would be used as part of a comprehensive verification framework, which may track nuclear warheads from deployment through dismantlement. A confirmation regime that involves verified dismantlement of nuclear weapons would provide the highest level of assurance that reductions are real. In particular, if the fissile materials that are recovered from dismantled warheads are placed under international safeguards or, better, eliminated or disposed-of, this regime would also provide the highest degree of irreversibility and ensure that recovered materials and components are not simply re-entering the weapons complex, where they could be used to make new weapons. While there remain technical challenges for warhead confirmation measurements, more important – and perhaps more difficult to achieve – may be the buy-in from nuclear weapon states to seriously consider verification approaches based on such measurements. International verification exercises, involving both weapon and non-weapon states, are one way to facilitate this process.

In the meantime, warhead dismantlements are taking place without any verification provisions. These are welcome activities, which accelerated after the end of the Cold War and continue to this day in some weapon states; at the same time, however, unverified dismantlement may create ambiguities for future arms control agreements that limit total stockpiles of nuclear weapons. While efforts toward first bilateral or multilateral all-warhead agreements are underway, it should be in the interest of all parties to document these dismantlements in ways that inspectors will find credible at later times.

Endnotes

1 J. Fuller, "Verification on the Road to Zero: Issues for Nuclear Warhead Dismantlement," *Arms Control Today, December 2010; Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, Committee on International Security and Arms Control, National Academy of Sciences, Washington, DC, 2005. Available: *https://www.nap.edu/catalog/11265/monitoring-nuclear-weapons-and-nuclear-explosive-materials-an-assessment-of*.

2 There may be ways to devise verification regimes that do not require baseline or other declarations. Since declarations are well established and non-controversial, we assume they would also be part of future all-warhead agreements. For a more detailed discussion of declarations, see Part II in *Working Group 4: Verification of Nuclear Weapons Declarations*, International Partnership for Disarmament Verification, April 2020. Available: *https://www.ipndv.org/wp-content/uploads/2020/04/WG4_Deliverable_FINAL.pdf*.

3 *Safeguards Techniques and Equipment: 2011 Edition*, International Nuclear Verification Series No. 1 (Rev. 2), International Atomic Energy Agency, Vienna, 2011.

4 R. G. Johnston, *Tamper-Indicating Seals: Practices, Problems, and Standards*, LAUR-03-0269, Los Alamos National Laboratory, 2003.

5 Johnston, 2003, *op. cit.*

6 Johnston, 2003, *op. cit.* In reviewing the United States efforts undertaken as part of the START process since the 1980s, James Fuller notes that "U.S. technologists assumed a very high degree of cheating sophistication available to the treaty partner... with unlimited budget and no inspecting party continuous presence." Jim Fuller, *The Quest for Extreme Security Unique Identifiers, 1986–1992*, April 2006. Available: *fissilematerials.org/library/jf06.pdf*.

7 R. G. Johnston and A. R. E. Garcia, "An Annotated Taxonomy of Tag and Seal Vulnerabilities," *Journal of Nuclear Materials Management*, 28 (3), Spring 2000.

8 G. Kuhn, *Experiencing the Impossible: The Science of Magic*, MIT Press, Cambridge, Massachusetts, 2019.

9 Sabotage during application can include: tagging and sealing the wrong container; failing to tag and seal all containers or failing to seal all entry/exit routes to a storage area; incorrectly applying a tag or seal; or containerizing the wrong item. Sabotage during readout can include: deliberately damaging the tag or seal and perhaps also the container to prevent detection of prior tampering; tampering with the readout device so that problems with tag or seal go unnoticed; or tampering with paperwork or computer records to create the illusion of honest mistakes (for example, by replacing a seal with a seal of a different type but with the same serial number).

10 E. R. Gerdes, R. G. Johnston, and J. E. Doyle, "A Proposed Approach for Monitoring Nuclear Warhead Dismantlement," *Science & Global Security*, 9 (2), 2001.

11 D. Krementz, R. Poland, and G. Weeks, "Mapping and Evaluation of Technologies for Maintaining Chain of Custody during a Nuclear Weapons Monitored Dismantlement," *57th Annual INMM Meeting, Atlanta*, Georgia, July 2016.

12 D. Blair and N. Rowe, *A Global Perspective on Continuity of Knowledge: Concepts and Challenges*, SAND2014-17676C, Sandia National Laboratories, Albuquerque, New Mexico, 2014. Available: *https://www.osti.gov/servlets/purl/1315149*.

13 H. A. Smartt and Z. N. Gastelum, *Tamper-Indicating Enclosures: A Current Survey*, SAND2015-4251C, Sandia National Laboratories, Albuquerque, New Mexico, 2015.

14 *Safeguards Techniques and Equipment*, 2011, *op. cit.*

15 Gerdes, Johnston, and Doyle, 2001, *op. cit.*

16 In a replay attack, a valid message or data stream is recorded and later fraudulently repeated so that an attack remains undetected. Most famously perhaps, Stuxnet used a replay attack while compromising Iran's Natanz enrichment plant in 2010.

17 D. K. Hauck, D. W. MacArthur, et al., "The Role of Portal Monitors in Arms Control and Development Needs," *53rd Annual INMM Meeting*, Orlando, Florida, July 2012.

18 NDA is also used as an abbreviation for non-destructive assay.

19 One challenge, further discussed below, is the possibility that gamma radiation can be effectively shielded (using lead and other high-Z materials). Inspections based on gamma measurements may therefore also have to confirm the absence of such shielding materials.

20 T. W. Crane and M. P. Baker, “Neutron Detectors,” Chapter 13 in Reilly et al., *Passive Nondestructive Assay of Nuclear Materials*, 1991.

21 H. A. Smith, Jr and M. Lucas, “Gamma-Ray Detectors,” Chapter 3 in D. Reilly, N. Ensslin, H. Smith, Jr., and S. Kreiner, *Passive Nondestructive Assay of Nuclear Materials*, LA-UR-90-732, NUREG/CR-5550, U.S. Nuclear Regulatory Commission, Washington, DC, 1991.

22 A party may even refrain from proposing certain attributes worrying that the mere suggestion of a particular attribute might reveal weapon features that the other party is unaware of.

23 D. Spears, ed., *Technology R&D for Arms Control*, U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Washington, DC, 2001; Y. Jie and A. Glaser, “Nuclear Warhead Verification: A Review of Attribute and Template Systems,” *Science & Global Security*, 23 (3), 2015.

24 C. Chen, C. Dale, S. DeLand, A. Waterworth, T. Edmunds, D. Keating, and M. Oster, “Developing a System Evaluation Methodology for a Warhead Monitoring System,” *57th Annual INMM Meeting*, July 2016, Atlanta, Georgia.

25 Consistent with this approach and for similar reasons, a recent report published by the International Partnership for Disarmament Verification (IPNDV) introduced the concept of “items declared as weapons.” *Working Group 4: Verification of Nuclear Weapons Declarations*, 2020, op. cit.

26 *Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms (“New START”)*, April 2010; *Radiation Detection Equipment: An Arms Control Verification Tool*, Product No. 211P, Defense Threat Reduction Agency, Fort Belvoir, VA, October 2011. Available: *https://www.hsdl.org/?abstract&did=715954*.

27 E. Lepowsky, J. Jeon, and A. Glaser, “Confirming the Absence of Nuclear Warheads Via Passive Gamma-Ray Measurements,” *Nuclear Instruments and Methods in Physics Research A*, 164983, December 2020.

28 For example, the host may not want to reveal the total background (gamma or neutron) radiation level in a certain facility; such a concern could be addressed with simple information barriers or by conducting the measurement in a separate building or environment.

29 S. Philippe, A. Glaser, and E. W. Felten, “A Cryptographic Escrow for Treaty Declarations and Step-by-Step Verification,” *Science & Global Security*, 27 (1), 2019.

30 T. Garwin, *Tagging Systems for Arms Control Verification*, Analytical Assessment Corporation, Sponsored Office Technology Assessment, Tech. Rep. AAC-TR-10401/80, Washington, DC, February 1980; S. Fetter and T. Garwin, “Using Tags to Monitor Numerical Limits,” in *Technology and the Limitation of International Conflict*, B. M. Blechman and Ed. Lanham, Foreign Policy Institute, Johns Hopkins University, Maryland, 1989.

31 C. Comley, M. Comley, P. Eggins, G. George, S. Holloway, M. Ley, P. Thompson, and K. Warburton, *Confidence, Security & Verification, The Challenge of Global Nuclear Weapons Arms Control*, AWE/TR/2000/001, Atomic Weapons Establishment, Aldermaston, United Kingdom, 2000. Available: *http://fissilematerials.org/library/awe00.pdf*; Arthur Tompkins, ed., *Provenance Research Today: Principles, Practice, and Problems*, Lund Humphries, London, 2020. A similar challenge exists in the arts and archaeology. “Perhaps the hardest thing of all to forge is provenance. A forger cannot alter the past as he can alter documents or material objects, and thus it is that forgeries often break down on provenance – the establishment of a chain of evidence (location, ownership, documentary record) that will lead securely back to the alleged source. [...] It is still neglected with surprising frequency, whereas scientific evidence can disprove the authenticity of ancient artifacts but very rarely prove it.” See: C. P. Jones, “A Syntax of Forgery,” *Proceedings of the American Philosophical Society*, 160, 2016.

32 K. Tolk, “Reflective Particle Technology for Identification of Critical Components,” *33rd Annual INMM Meeting*, Orlando, Florida, July 1992; H. A. Smartt et al., “Status of Non-contact Handheld Imager for Reflective Particle Tags,” *55th Annual INMM Meeting*, Atlanta, GA, July 2014.

33 S. D. Drell, et al., *Verification Technology: Unclassified Version*, JASON Report, JSR-89-100A, The MITRE Corporation, McLean, VA, October 1990. Available: *https://fas.org/irp/agency/dod/jason/verif.pdf*; Sabina E. Jordan, *Buddy Tag’s Motion Sensing and Analysis Subsystem*, Sandia National Laboratory, Albuquerque, New Mexico, 1991; A. Glaser and M. Kütt, “Verifying Deep Reductions in the Nuclear Arsenals: Development and Demonstration of a Motion-detection Subsystem for a “Buddy Tag” Using Non-export Controlled Accelerometers,” *IEEE Sensors Journal*, 20 (13), 2020.

34 S. Fetter, “Nuclear Archaeology: Verifying Declarations of Fissile-Material Production,” *Science & Global Security*, 3 (3–4), 1993; T. W. Wood, B. D. Reid, C. M. Toomey, K. Krishnaswami, K. A. Burns, L. O. Casazza, D. S. Daly and L. L. Duckworth, “The Future of Nuclear Archaeology: Reducing Legacy Risks of Weapons Fissile Material,” *Science & Global Security*, 22 (1), 2014.

35 Some information considered sensitive could be masked by working with “blend stocks” (as has been the case for the Plutonium Management and Disposition Agreement between Russia and the United States).

36 T. B. Taylor, “Verified elimination of nuclear warheads,” *Science & Global Security*, 1 (1–2), 1989. Taylor further elaborates on the idea by proposing that “each owner nation could mask the true value of quantities it wished to keep secret by adding appropriate items, in unrevealed amounts, to the objects to be dismantled. An example would be the addition of a large weight of sand to each of the containers for some type of warhead, without ever revealing what that weight was.”