Federal Foreign Office

Toward Nuclear Disarmament

Building up Transparency and Verification

MALTE GÖTTSCHE AND ALEXANDER GLASER (EDITORS)

Federal Foreign Office

Toward Nuclear Disarmament

Building up Transparency and Verification

MALTE GÖTTSCHE AND ALEXANDER GLASER (EDITORS)

Content

Foreword

AMBASSADOR RÜDIGER BOHN

Transparency and compliance mechanisms of future disarmament agreements are necessary to create a positive momentum in a strained international arms control and disarmament environment. Especially in the absence of tangible progress on the issue of comprehensive reductions of nuclear arsenals, intermediate steps such as limitations on fissile material production (FMCT) or nuclear testing (CTBT) as well as progress on risk reduction are of paramount significance. Rapid technological progress in the development of new weapons systems that are still largely unregulated (Artificial Intelligence, Lethal Autonomous Weapons Systems, Space Weapons, Hypersonics) present new challenges to arms control and disarmament and have potential destabilizing effects.

Given these challenges, it is all the more important – in light of the 50th anniversary of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and with a view on the upcoming NPT Review Conference – to send a positive signal for the preservation of the nuclear order, to build bridges between Nuclear Weapon States and Non-Nuclear Weapon States, and to work out concrete measures and reach progress for a step-by-step approach to nuclear disarmament.

The field of Nuclear Disarmament Verification is particularly appropriate for this purpose. It can help to prepare the ground and foster political approximation on more general issues regarding future nuclear arms control and reductions.

Henry Kissinger and Sam Nunn aptly summed up the importance of Nuclear Disarmament Verification in a joint article for the New York Times in 2007: “A world without nuclear weapons will not simply look like today’s world minus nuclear weapons, but in such a world there must be a sustainable and resilient mechanism of cooperative security including a robust verification system”.

Preparatory work for such a mechanism must begin now. To achieve significant reductions in nuclear arsenals in the future, the development and practical testing of verification procedures and arrangements are essential. Conceptual and methodological issues as well as technical aspects must be taken into account. Such work serves our political interest in demonstrating that no unsurmountable hurdles exist for credible multilateral nuclear disarmament, and in providing a platform for the notion that the future of nuclear arms control and disarmament is multilateral.

Any new efforts and initiatives in the field of Nuclear Disarmament Verification could draw on knowledge and expertise gained through the implementation of former and current bilateral and multilateral treaties and regimes. The same applies to a number of recent initiatives including the “International Partnership for Nuclear Disarmament Verification”, the German-French “NuDiVe” exercise, the “Quad Initiative” (Norway, Sweden, United Kingdom, United States) and last but not least the “United Nations Group of Governmental Experts on Nuclear Disarmament Verification”.

Over years, the Government of the Federal Republic of Germany has been strongly involved in the conceptual and practical development of different aspects of Nuclear Disarmament Verification. This report illustrates these continuous efforts. It presents fresh ideas and new approaches of several renowned scholars and will – we hope – serve as a meaningful and timely contribution to the important debate on how to advance nuclear arms control in the years to come.

Ambassador Rüdiger Bohn,
Deputy Federal Government Commissioner for Disarmament and Arms Control,
Federal Foreign Office

Executive Summary

Despite or precisely because of the current crisis of nuclear arms control, it is pressing to sketch potential pathways on how to get back on a track of reductions in weapon arsenals, eventually making progress towards disarmament. As a requirement for such a process to succeed and be sustainable, having effective and widely accepted verification tools available is crucial.

Technical studies on how to verify nuclear disarmament have been published for over two decades. Among the most notable ones are a study by the U.S. National Academy of Sciences' Committee on International Security and Arms Control,[1] a report by the International Panel on Fissile Materials,[2] and several books.[3] The Nuclear Threat Initiative convened an international expert group,[4] and several bilateral and multilateral initiatives have contributed to the debate, in particular the Trilateral Initiative[5] and the U.K.-Norway Initiative.[6] Current multilateral fora include the Quad Nuclear Verification Partnership[7] and the International Partnership for Nuclear Disarmament Verification.[8]

With this report, we pursue two goals. First, we seek to build upon the previous work to provide an overview of what we consider likely to be the technical main elements of disarmament verification. By examining the current state-of-the-art of verification technology, we identify those areas where verification technologies and concepts are readily available – thus providing an update to prior studies – and areas where gaps need to be addressed both by further scientific research and preparatory measures by governments.

Verification at low warhead numbers will likely be comprehensive and rigorous. Progress toward nuclear disarmament should be difficult to reverse. Corresponding monitoring arrangements can be expected to become more comprehensive the smaller arsenals become. While current research – such as work on warhead confirmation measurements using information barriers – focuses on these long-term challenges, it is equally important to think about what kind of measures would be required and could be implemented as next steps.

Therefore, the second goal of this report is to highlight the spectrum of monitoring and transparency options: comprehensive and complex verification measures are at the long-term end; on the other end are much simpler non-intrusive steps that could be pursued in the shorter term given political will. Such initiatives could but do not have to be legally binding. They would contribute to confidence-building and lay the basis for further measures along the way. Notably, in 2019, the Group of Governmental Experts on nuclear disarmament verification concluded that "confidence-building measures may complement nuclear disarmament verification arrangements between the implementing parties of a specific treaty."[9]

The objective of monitoring is to confirm declared activities and to confirm with high confidence the absence of undeclared facilities, stocks, and activities. The starting point of verification regimes is for a state to issue a baseline declaration, covering those elements limited by an agreement. In the chapter *Baseline Declarations,* Mona Dreicer examines how such declarations would fit into the larger disarmament framework. She proposes that narrow and unverifiable declarations could be issued initially as part or even independent of an agreement to begin a confidence-building process, with states increasing the level of detail once they are ready to do so. In an appendix, Sébastien Philippe offers a related technology-based approach, where states could provide detailed declarations in a secure manner upfront, but only reveal their content to inspectors gradually as required by the agreement and as confidence in the process increases over time.

Verification of arms-control agreements that place limits on all weapons in the stockpiles are likely to face some fundamentally new challenges and may require new verification approaches. In the chapter *Monitoring Regimes for All-Warhead Agreements*, Alexander Glaser proposes 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. Only the third phase would require actual warhead measurements, but it may well be that parties will consider a regime without such measurements adequate for deep cuts in the nuclear arsenals.

In their chapter *Fissile Material Stocks and Production*, Sharon Squassoni and Malte Göttsche find that the current IAEA safeguards toolbox will be insufficient for verification in weapon states. Significant challenges arise from the fact that those states produced and kept large stocks of fissile materials without international monitoring. Reconstructing their fissile material production histories ("nuclear archaeology") will be essential. While related methods need to be further developed and demonstrated, the chapter discusses how to build initial confidence in this area and prepare the ground for future fissile material monitoring. Such activities could ease future verification challenges and perhaps allow for less intrusiveness later-on.

Onsite inspections will play a central role both for warhead and fissile material monitoring and have so far not only been implemented on a routine basis in IAEA safeguards, but also in U.S.-Russian arms control. Other weapon states have less experience and may be more reluctant to agree to such inspections, especially early on. Irmgard Niemeyer and Alexander Glaser examine the potential of remote and standoff monitoring technologies in the context of fissile material production and warhead monitoring, including satellite imagery, wide-area environmental monitoring, and perimeter monitoring. Indeed, they argue in their chapter *Nuclear Monitoring and Verification Without Onsite Access*, there might be some room for complementing or reducing the role of onsite inspections by applying such measures.

Verification efforts might also need to focus on the entire nuclear weapons enterprise, as Moritz Kütt discusses in his chapter *Weapons Production and Research*, which includes facilities to assemble and disassemble weapons, manufacture components, as well as research, development and testing infrastructure. Possible verification approaches would ensure that facilities no longer operate, confirm their elimination, certify their conversion, and detect undeclared facilities. Much further research is necessary to develop appropriate verification approaches in these areas. As a starting point, shut-down facilities could be used as test beds to prepare scientists, inspectors as well as policy makers for the challenges of more comprehensive measures once respective agreements have been negotiated.

Finally, in their *Conclusion: Building Up Transparency and Verification*, Malte Göttsche and Alexander Glaser find that it is important not to narrow down the available verification options too quickly. There is not *the* one way or *the* one central aspect of how to verify disarmament. Furthermore, it is important to seek input from a broad range of stakeholders – ideally, also including all nuclear weapon states –about their ideas for how to approach the challenge. Their specific findings are:

1. A future international exercise should focus on verifying the absence of nuclear weapons, the most urgent and immediately useful verification task. This could be an opportunity to involve Russia, China, and possibly other weapon states.
2. In addition to formal verification, transparency measures play a key role to ensure that the confidence required for disarmament is obtainable. They should be introduced gradually using smart approaches – starting today.
3. The discussion of nuclear disarmament verification must be significantly broadened beyond warhead dismantlement and, in particular, place greater emphasis on monitoring fissile materials. In general, verification approaches that support the irreversibility of disarmament, but are at the same time as non-intrusive as possible, should be prioritized.
4. Gaps in scientific methods and technology for disarmament verification can only be closed with a sustained commitment to research and development. International collaboration can be facilitated by a Group of Scientific and Technical Experts and joint experiments.

Given the complex research tasks, only a strong and continuous engagement can ensure that methods and technologies will be available when they are needed. Only if this is planned with foresight, will there be sufficient time to address all issues necessary to enable deep cuts and move toward a world without nuclear weapons.

Endnotes

1 *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, Committee on International Security and Arms Control, National Academies Press, 2005.

2 *Global Fissile Material Report 2009*, International Panel on Fissile Materials, 2009.

3 C. Hinderstein (ed.), *Cultivating Confidence*, Nuclear Threat Initiative, 2010; T. Shea, *Verifying Nuclear Disarmament*, Routledge, 2019; I. Niemeyer, M. Dreicer and G. Stein (ed.), *Nuclear Non-proliferation and Arms Control Verification,* Springer, 2020.

4 *Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks*, Nuclear Threat Initiative, 2014. Available: *https://www.nti.org/analysis/reports/innovating-verification-new-tools-new-actors-reduce-nuclear-risks/*.

5 T. Shea, "Report on the Trilateral Initiative," *IAEA Bulletin 43/4,* 2001.

6 see *https://ukni.info/*.

7 see *https://quad-nvp.info/*.

8 see *https://www.ipndv.org/*.

9 *Final report of the Group of Governmental Experts to consider the role of verification in advancing nuclear disarmament,* United Nations, A/74/90, 2019, p. 14.

1. Baseline Declarations

MONA DREICER

ABSTRACT. *Verifying activities in a state's dynamic nuclear enterprise to achieve sufficient confidence in compliance with arms reduction or disarmament commitments is a grand challenge. The declared baseline of stockpiles of materials, production facilities, and numbers of warheads set the foundation for verifying treaty compliance. Over the past three decades, there have been quite a number of proposals for the form and content of baseline declarations together with possible methods of verification – whether addressing part of the nuclear enterprise or encompassing the whole national system (some of these are briefly presented here). Depending on the provisions of the particular agreement, an initial narrow declaration could suffice, and be enlarged as parties agree to include additional details. As limitations and reductions become more stringent, increasingly detailed information would be required. The current research program includes a broad range of expertise, looking beyond nuclear weapon states to non-nuclear weapon states, non-governmental organizations and academia to bring new perspectives, expand beyond traditional thinking and improve the content and verification of baseline declarations.*

Introduction

Baseline declarations are the foundation of a verification regime for any treaty whether it is aimed at reductions, limitations or elimination of nuclear weapons. The complexity of a state's nuclear weapons enterprise, even if it does not have a long history of holding nuclear weapons, and the national security implications of sharing information, complicate declaring existing inventories. Any declarations will be tailored to the specific conditions agreed between the parties, and the level of detail will reflect the scope of the agreement's object and purpose, as well as the intrusiveness of the verification regime. Baseline declarations must not necessarily be made in the context of bi- or multi-lateral legal commitments. A declaration issued by an individual state can be taken as a first step – shedding light into parts, if not all, of a nuclear enterprise as an initial confidence-building measure prior to a more complete, higher-confidence verification regime. Such a voluntary measure would, however, not be verifiable.

Traditional arms control agreements focus on a portion of the enterprise, with the declarations clearly defined and linked to the purpose of the treaty. If total disarmament is the goal, then ultimately the declarations must include a vast amount of information, including the history of all past weapons-related activities so that both the correctness and completeness of the declarations can be ascertained. The declared baseline of stockpiles of materials, production facilities, and numbers of warheads will set the basis for verifying the steps taken towards disarmament. These declarations must also include accounting of military and all civilian fuel cycle capabilities, which are not currently under IAEA safeguards in nuclear weapons states (see chapter *Fissile Material Stocks and Production*).

Such a broad and intrusive verification regime will be essential to ensure that a state has not maintained an undeclared secret stockpile or maintained active re-armament capabilities. Achieving sufficient confidence that cheating would be detected on a state-wide level is a complex and complicated task and is the central element of disarmament.[1] Over the past three decades, there have been quite a number of proposals for the form and content of baseline declarations – whether addressing part of the nuclear enterprise or encompassing the whole national system. A number of important questions are consistently raised:

- Is it possible to verify actual physical warheads rather than agreeing on counting rules as used in the START treaties (e.g. assuming a set number of warheads per delivery system without verification of the warhead number)? Can a definition of a warhead be agreed? Do we have the right technology to do the job?
- How can classified or military information and access deemed essential for national security be protected? How can we verify with confidence while blocking/protecting sensitive information? How can non-nuclear weapon states be involved without sharing weapons information?
- Even with detailed and intrusive declarations to provide increased confidence – will it be possible to verify correctness and completeness to provide States with sufficient confidence? Can states provide the historic documentation about production, use, and disposal that will be needed? Will the available historical information be sufficient?
- Is it possible to design a progressive release of information over time that will achieve the required trust and confidence?

To mitigate the national security obstacles and/or a state's lack of experience with arms control treaties and transparency, declarations could begin at the more general unverifiable level and become more specific over time. Depending on the provisions of the particular agreement, an initial narrow declaration could suffice, and be enlarged as parties agree to include additional details. As limitations and reductions become more stringent, more detailed information would be required. However, to begin states could unilaterally declare their total warhead and weapons-usable material inventories, in aggregate, simply as three top-level numbers: the total inventories of warheads, highly enriched uranium (HEU), and separated plutonium.

Material inventory information has been released and compiled in support of securing, reducing and eliminating fissile materials available to be used in nuclear weapons. Since 2006 the International Panel on Fissile Materials (IPFM) has been reporting on Global Fissile Material[2] stocks based on national reports, such as the United States government[3] and other open sources. Aggregate total inventory numbers of nuclear weapons have been reported by the United States, France and the United Kingdom, and other estimates are provided by the IPFM and other sources[4]. Declarations for all states with nuclear weapons programs would be a next important step.

Treaty Declarations

As stated earlier, the declarations would be aligned with the object and purpose of the treaty or agreement. The initial baseline declaration will be the snapshot of treaty accountable items or materials at the time of entry-into-force. Once declared, the baseline is verified by the inspection regime and regularly updated while the treaty is in-force. Although often a challenging negotiation point, the definition of treaty accountable items will determine the structure of the verification regime. Each state's confidence in accuracy of the declarations establish and then maintain the confidence in treaty compliance over time. In the past, the United States and Russia relied on their own national technical means to support verification. With greater multilateral engagement with countries of varying resources, the cooperative regime will be an important aspect of maintaining confidence.[5]

If states parties are reluctant to declare and verify comprehensive information initially, details for only portions of the enterprise would offer a narrower baseline declaration but could be designed as a stepping-stone towards future agreements with a broader set of declarations. Alternative arrangements could, for example, include agreements that only require the declaration and verification of deployed warheads, or a subsection of its weapons-usable material holdings, such as plutonium recovered through dismantlement of retired warheads. Nevertheless, declarations of material by type (plutonium or highly enriched uranium) or use, combined with an intrusive verification regime, would provide the greatest confidence in compliance. There have also been proposals on ways that regimes could defer open declarations by initially encrypting them, as described by Sébastien Philippe in the attached annex, or defer high-confidence verification.[6] Trust would be built up through time.

It is pretty clear that today, enterprise-wide transparency and verifiability cannot be accomplished in one wide-reaching treaty. Different parts of the system must be addressed in a step-by-step progressive approach and declarations will ultimately need to be expanded to a very large framework that includes all parts of a nuclear weapons enterprise in a state – way beyond delivery vehicles and weapons deployed on delivery vehicles as in New START. For a complete understanding of the baseline, the history of all aspects of the enterprise, including material production and use, warhead production and dismantlement (comprising the total stockpile of weapons and components), and warhead inventories in all stages of deployment, storage or awaiting final disposition, will need to be declared. All of these activities are likely to have been situated across a wide range of facilities and locations through time.[7]

Options for warhead baseline declarations could be approached in a number of ways, with different degrees of detail. Examples are: to declare fully assembled warheads that could be counted along with nuclear subcomponents, such as pits and secondaries; warheads and their components could be grouped by type or status (e.g., deployed, non-deployed, or reserve); and/or information about the warhead deployment, production and storage sites/facilities could be included in an inventory declaration.[8]

In 2005, a National Academy of Sciences report[9] outlined examples of information that could be included in declarations of weapon inventories in four progressive levels of detail outlining a possible step-by-step approach that would increase the level of intrusiveness gradually (see textbox).

1. Current total number of nuclear weapons of all types. Each year since first test: total number assembled, disassembled, and in the stockpile. For each of next five years: planned number assembled, disassembled, stockpiled.

2. Current total number of each weapon type, by status (e.g., operationally deployed, active reserve, inactive reserve, retired/awaiting dismantling). Delivery systems associated with each weapon type. Each year since first test: total number of each weapon type assembled, disassembled, and in the stockpile. For each of next five years: planned number of each type assembled, disassembled, and in the stockpile.

3. Name and location of all facilities at which nuclear weapons are currently deployed, stored, assembled, maintained, remanufactured, dismantled, or other otherwise handled. Facility descriptions and site maps indicating each launcher, storage bunker, building, or other site in which nuclear weapons are or may be located. Number of each weapon type at each facility. Name and location of facilities that previously contained weapons.

4. For each weapon: serial number, weapon type, status, and current location.

The report went on to explain that declarations of historical weapon inventories would help build confidence in the accuracy and completeness of declarations of current inventories, as well as declaring future plans for the weapon stockpile, and the projected number of weapons to be assembled and dismantled each year for the next few years.

More recently an international initiative, involving both states with and without nuclear weapons, the International Partnership on Disarmament Verification (IPNDV), reported on the results of their work to develop mechanisms to verify nuclear weapons declarations.[10] They considered four disarmament categories to help bound the range of characteristics that would be needed for verifying declarations. These categories are (1) reductions in nuclear weapons numbers, (2) limitations on nuclear weapons numbers, (3) reaching global zero, and (4) maintaining global zero.

- For a *reductions* treaty focused on dismantlement, initial declarations would include the numbers and types of nuclear weapons to be dismantled/reduced, the deployment site or storage facility, the transportation method, the transport of the dismantled components, and the monitored storage facilities. The location of the deployment site, the dismantlement facility, and the disposition site would also be important.
- For a *limitations* treaty, the total number of weapons must be verified. An initial declaration would need to include the total number of existing nuclear weapons and the number of weapons assigned for dismantlement, including their location and operative status. Information about the location would include the deployment, storage, or production site. To verify that no undeclared production of weapons or weapons production facilities exist, these would have to be included in declarations so that any new weapons would be accounted for in declarations.
- To *reach global zero*, an initial baseline declaration would include timely information about the number of remaining nuclear weapons to be dismantled, including nuclear-capable delivery systems, and ideally facilities/locations of the entire nuclear weapons cycle must be declared. Civilian and military nuclear fuel cycles would need to be safeguarded so that material balance could be achieved, therefore requiring material declarations.

To achieve and *maintain* "zero" it will be necessary to verify nuclear material baseline declarations in addition to warhead declarations. This accounting reported by specific categories and uses should include totals and uncertainties. This will provide the foundations for monitoring and detection of any material diversion to weapons uses. An example baseline declaration of weapons-usable nuclear material was proposed by a working group of the Nuclear Threat Initiative (NTI)[11], see table.

Material Baseline Declaration		Plutonium		HEU	
		Weapons-grade	Non-weapons-grade	Weapons-grade	Non-weapons-grade
Materials in warheads	UIR*				
Materials in stocks available for warheads	UIR				
	IR*				
Materials in naval programs	UIR				
	IR				
Materials in other uses	UIR				
	IR				
Materials declared excess	UIR				
	IR				
Total Materials					
military programs	UIR				
	IR				
civil programs	UIR				

Example baseline declaration of weapons-usable nuclear materials. * UIR = unirradiated, IR = irradiated (e.g. fuel in reactors or spent fuel in storage). More details on the definitions can be found in the report *Verifying Baseline Declarations of Nuclear Warheads and Materials*, Nuclear Threat Initiative, 2014.

Consistent reporting across parties will require clear definitions of the materials, which must be agreed in advance of the declarations. Even with detailed declarations, considerable uncertainty will remain as a result of inconsistent or incomplete past record keeping methods and material unaccounted for as part of the production processes – this is a common source of uncertainty in large process facilities. Possible preparatory activities that governments could undertake to prepare for making baseline declarations are outlined in the NTI report.[12]

Verification Challenges and How to Address Them

Earlier, much of the focus of disarmament research and development was on the verification of nuclear weapons' dismantlement, beginning at the time of U.S.-Russia negotiations for START II and START III and exclusively conducted by nuclear weapons states. In support of material disposition agreements, there was some effort to determine how to verify that the material slated for final disposition originated from dismantled nuclear weapons rather than from existing material stockpiles. The priority was not to improve verification of baseline warheads or materials declarations.

R&D focused on verifying whether an object in a container was a nuclear warhead or not – while addressing the security (classification, managed access) and safety concerns that impeded direct measurements. Using very fundamental radiation detection techniques, the lack of a warhead is verified during New START inspections, but improved methods to discriminate a warhead from other radiation signatures will be needed for baseline declaration verification and detection of clandestine warhead stockpiles.

Past key areas of research have been to develop *attribute, template* and *managed access* techniques that could identify a warhead with limited information. In more recent years, R&D programs have focused *uniquely identifying treaty accountable items,* maintaining *chain of custody* (tags and seals, tamper indicating devices), and *information barriers* (the collection of verification information absent any sensitive weapons information). However important confidence in item and inventory tracking is to the overall regime, it must be based on confidence on the authenticity of the item from the beginning of the verification process (at the baseline). Recent research has taken new approaches to identifying warheads. New *Zero Knowledge* protocols propose a promising method to identify items as nuclear weapons while protecting weapons information. Some of these concepts are presented in the chapter *Monitoring Regimes for All-Warhead Agreements*. *Cryptographic* data techniques mentioned earlier can allow for partial declaration as countries progressively move towards more intrusive verification regimes. Other areas where continued R&D would improve understanding of exiting material inventories for baseline declarations are reconciling past accounting uncertainties and *nuclear archeology* to reconstruct historic nuclear material production.

Verifying activities in a state's dynamic nuclear enterprise to achieve sufficient confidence in compliance with disarmament commitments is a grand challenge. Accurate verifiable baseline declarations are needed as the basis for a successful verification regime that can detect significant noncompliance and to ensure that "breakout" cannot be easily achieved.

As states without nuclear weapons pressure nuclear weapon states to increase their disarmament efforts, they have become more actively engaged in understanding and developing verification regimes, as seen by the enthusiastic participation in the IPNDV. The research programs being conducted with a broader range of expertise looking beyond nuclear weapon states to non-nuclear weapon states, non-governmental organizations and academia will bring new perspectives intended to break loose more traditional thinking and improve baseline verification capabilities.

Endnotes

1 J. Goodby and S. Pifer, *A World Without Nuclear Weapons*, Hoover Institution, 2015. Available: *https://www.hoover.org/research/world-without-nuclear-weapons*.
J.M. Acton, "Fissile Materials and Disarmament: Long-term, Short-term Steps" in C.M. Kelleher and J. Reppy, eds., *Getting to Zero: The Path to Nuclear Disarmament*, Stanford University Press, 2011.

2 *Global Fissile Materials Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production*, International Panel on Fissile Materials, 2015. Available: *http://fissilematerials.org/library/gfmr15.pdf*.

3 *Transparency in the U.S. Highly Enriched Uranium Inventory*, White House Office of the Press Secretary, March 16, 2016. Available: *https://obamawhitehouse.archives.gov/the-press-office/2016/03/31/fact-sheet-transparency-us-highly-enriched-uranium-inventory*; *The United States Plutonium Balance, 1944-2009*, U.S. Department of Energy, 2012.

4 *https://www.nti.org/learn/countries/*.

5 The cooperative verification capabilities provided by the Provisional Technical Secretariat of the Comprehensive Test Ban Treaty Organization are an example of a robust cooperative verification regime available to all States Parties.

6 P. Podvig and R. Snyder, *Watch them Go: Simplifying the Elimination of Fissile Materials and Nuclear Weapons*, UNIDIR, 2019.

7 *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*.

8 *Verifying Baseline Declarations of Nuclear Warheads and Materials*, Nuclear Threat Initiative, 2014. Available: *https://media.nti.org/pdfs/WG1_Verifying_Baseline_Declarations_FINAL.pdf*.

9 *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, 2005, op. cit., p. 52.

10 "Part I. Introduction to the Verification of Nuclear Weapons Declarations," in *IPNDV Working Group 4 Deliverable*, International Partnership for Nuclear Disarmament Verification, 2019. Available: *https://www.ipndv.org/wp-content/uploads/2020/04/WG4_Deliverable_FINAL.pdf*.

11 *Verifying Baseline Declarations of Nuclear Warheads and Materials*, 2014, op. cit., p. 52.

12 *Verifying Baseline Declarations of Nuclear Warheads and Materials*, 2014, op. cit., p. 69.

1.a Appendix: Secure Declarations

SÉBASTIEN PHILIPPE

ABSTRACT. *The verification of arms control and disarmament agreements requires states to provide declarations, including information on sensitive military sites and assets, which are then verified for their correctness and completeness.*[1] *There are important cases, however, where states are reluctant to provide any such data, because of concerns about prematurely handing over militarily significant information before an agreement is reached. To address this challenge, this note discusses how established cryptographic tools can be leveraged to construct verifiable secure declarations of nuclear sites and assets that commit states to their content and at the same time protect sensitive information until they feel comfortable sharing it.*

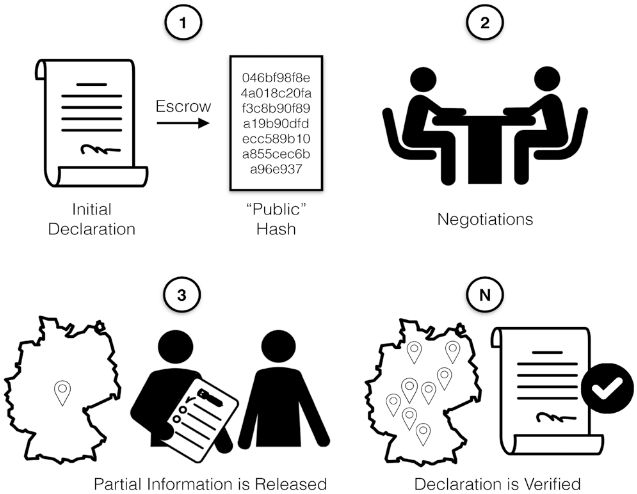
Introduction

Ever since the Strategic Arms Limitation Talks between the United States and the Soviet Union, nuclear arms control and reduction treaties have involved transparency measures and the exchange of information.[2] Negotiating deeper cuts and perhaps eliminating all nuclear weapons in nuclear arsenals may, however, require unprecedented disclosures in the form of baseline declarations (see chapter *Baseline Declarations*). Depending on the level of trust between state parties to future disarmament agreements, such disclosures may be difficult to undertake. One reason is that some states may perceive them as providing competitors with military significant information at an early stage in a process that could take several years if not decades to complete.

For some states that have long relied on secrecy and ambiguity as part of their nuclear deterrent strategy, agreeing to such demands may seem risky: it could provide competitors with a potentially comprehensive map of their military and nuclear weapons-related assets at a very early stage in the diplomatic process, which could become an important security concern if negotiations were to collapse. But given the international community's commitment to verifiable disarmament, it is difficult to conceive any successful diplomatic outcome that would not rely on verifiable declarations.[3] It is therefore fundamental to explore concepts and approaches that could address this challenge in order to facilitate future agreements, and signal states commitment to a process of verified disarmament.

One possible technical solution relies on the use of already established cryptographic techniques and could therefore be implemented rapidly.[4] It builds upon the concept of secure declarations proposed in a 2005 U.S. National Academy of Science study.[5] The approach is based on a secure information-sharing mechanism, which can be thought of as an escrow.

Loosely speaking, in such a scheme, a state places information inside a safe and locks it. It then shares the custody of the safe with others. The safe cannot be forced open, so no one can obtain the information unless the state decides to open it. Furthermore, for technical reasons it is infeasible for the state to alter or exchange the content of the safe when it opens it.



Using a cryptographic escrow in an inspection regime. (1) A detailed initial declaration is produced by the inspected party and placed in an escrow. A cryptographic commitment ("hash") to this declaration is made available. (2) The negotiations are ongoing. The escrow is built such that is possible to reveal only partial information at a time. (3) Prior to an on-site inspection, partial information about a site (location, status and items) is revealed to the inspecting party. The inspections eventually confirm the correctness of this information. (N) As negotiations move forward, information is released incrementally until the complete declaration is revealed. Only then the inspecting party has a complete picture of the inspected party assets.

More technically, a procedure ("hashing") is used to transform the original data ("cleartext") into a meaningless combination of characters ("hash") shown to the inspectors. States can then sequentially reveal relevant parts of that sensitive information to others when they choose to, by providing the cleartext and information on how this piece of information had been hashed. This allows other states to see that the revealed information was actually part of the original data, as they can now run the transformation themself and see whether they get the same hash. At the same, the mechanism is such that it is not feasible for states to alter the originally stored information in a way that the hash fully visible to inspectors would remain the same. That way, other states can be confident that the exact same information revealed later had already been contained in the declaration earlier. This mechanism therefore requires a state to commit itself to the correctness and completeness of its initial declaration at the outset, potentially even before negotiations start (see figure above).

Applications to Disarmament Verification

Verification of a freeze scenario

In the context of a verified disarmament process following a step-by-step approach,[6] a state could agree on freezing the production of fissile materials and components for weapons as well as on monitored storage of existing weapons as a first step. Under this framework, the state would produce a complete escrow of all production, storage, and deployment sites of nuclear weapons, missiles, and associated components. It would then commit to the inventories at each site (provide the hash) and agree not to move assets between sites. (Movement patterns between sites could be monitored with satellites.)

To verify correctness of the declaration, the state would invite inspectors to perform on-site inspections and verify that the assets and information declared in the escrow are present and valid. During these inspections, accountable items could be tagged with unique identifiers,[7] and other state parties would become more confident that a freeze is indeed in effect and that the rest of the declaration, which has yet to be revealed, is correct.

Confidence from the inspector's point of view would increase if sites could be picked at random,[8] although the host state may prefer to reveal the location and inventories at each site in the order it decides, for example starting with sites that are already known or considered less sensitive. Because each site can be revealed without compromising others, the pace of inspections can be adapted to the political process, making this approach well suited for an "action for action" negotiating process, where both sides would make incremental concessions working towards an ultimate settlement.

Combining the properties of the escrow and the possibility to perform challenge inspections would facilitate the process of establishing completeness of the declaration. If a member state believes it has detected proscribed activities at an undeclared site, the host state could prove whether or not it has included this specific site in the escrow. If a site is contained in the declaration, the state could disclose the part that contains just the location of the site, while not revealing any further information on that site. Both parties would wait and plan for a future inspection to confirm the correctness of the declaration. If the site is not in the escrow, a special inspection would have to take place to demonstrate that no proscribed activities are taking place at the site. Given the risk of exposure, it would be in the interest of the host state to produce a complete declaration from the very beginning.

Verification of numerical limits

The escrow can also be adapted to make commitments about items, bulk materials, and sites on a periodic basis. In the context of an agreement placing numerical limits on all nuclear weapons, treaty parties would regularly (for example, every 48 hours) exchange declarations with exactly one entry for each treaty accountable item. These declarations could be made public as they do not contain any information besides the total number of declared items, i.e., the number of rows in these declarations.

It is worth noting that the United States has already declared the exact number of nuclear warheads in its arsenal. In September 2014, this number stood at 4,717. Similarly, the United Kingdom and France have given upper ceilings that are generally considered very close to the actual values. Making declarations as considered here would not be without precedent and could reaffirm existing transparency measures.

Here and below, we assume that parties would be reluctant to provide the exact breakdown of storage locations for the treaty accountable items in their inventories. This could be due to security concerns or due to the fact that an adversary might be able to infer operational information that the host considers sensitive (and are not accessible by other means – for example space-based or airborne sensors). Using a cryptographic escrow scheme could avoid this concern.

Step 1: Inspection Initiation and Site/Item Selection. In preparation for an on-site inspection and based on the most recent available declaration, the inspecting party would first announce the storage or deployment location that it would like to inspect. At that point, a stand-down for the relevant site would take effect, which could be verified by national technical or other means. Alternatively, the inspecting party could simply pick one entry from the hashed declaration at random, i.e., without knowing the name or type of the site that will ultimately be inspected. Once the site is revealed, the host would then also reveal all other entries for the same site. Again, a stand-down for this site would take effect.

Step 2: Provision of Cleartext by Host. The host party would then provide the cleartext for all treaty accountable items that are present at the selected site. The inspecting party can now confirm that the cleartext entries produce the correct hash for all items. Note that in practice, this scheme does not require disclosing the exact number of treaty accountable items. The number of rows in the declaration is only an upper bound on the number of items. In this case, the list can be padded by adding dummy entries or duplicate entries for the same item. The declaring party must then be careful not to open more than one entry from the set of duplicates.

Step 3: On-Site Inspection to Confirm Cleartext Entries. The inspector team can now proceed to the site itself. Once the team arrives at the site, the host would present the declared treaty accountable items. Procedures would have to be available to confirm that additional objects that could be mistaken for nuclear warheads are in fact not treaty accountable (see chapter *Monitoring Regimes for All-Warhead Agreements*). Special casing or shrouds could be added to the treaty-accountable items to avoid visual cues. Inspectors may also be allowed to access other areas to gain confidence in the absence of undeclared treaty accountable items at the site.

Note that, in this most basic cryptographic escrow scheme, no tags whatsoever are required; and yet, declarations could over time provide high confidence in the correctness of the warhead declarations made by the parties of a treaty. As already mentioned, declarations could also include additional information that is not necessarily revealed in the initial stages of an agreement (such as serial numbers or perhaps even the amounts of special nuclear material in particular warhead types). Disclosure of these entries in the future could further increase the confidence in the correctness and completeness of the declarations, potentially reaching back for years or decades.

Endnotes

1 This chapter is based on a revised version of S. Philippe, A. Glaser and E.W. Felten. “A Cryptographic Escrow for Treaty Declarations and Step-by-Step Verification.” *Science & Global Security 27 (2)*, 2019.

2 J. Newhouse, *Cold Dawn: The story of SALT, Pergamon, 1989.*

3 T. Patton, S. Philippe, and Z. Mian. “Fit for Purpose: An Evolutionary Strategy for the Implementation and Verification of the Treaty on the Prohibition of Nuclear Weapons,” *Journal for Peace and Nuclear Disarmament*, 2 (2), 2019, pp. 387-409.

4 The technical details are provided in S. Philippe, A. Glaser and E.W. Felten, 2019, op. cit.

5 *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, Committee on International Security and Arms Control, National Academies Press, 2005, pp. 92–94.

6 A. Glaser and Z. Mian, “Denuclearizing North Korea: A verified, phased approach,” *Science*, 361(6406), 2018, pp. 981–983.

7 S. Fetter and T. Garwin, “Using tags to monitor numerical limits in arms control agreements,” in B.M. Blechman, ed., *Technology and the Limitation of International Conflict*, Johns Hopkins University Foreign Policy Institute, University Press of America, 1989, pp. 33–54.

8 D. M. Kilgour, “Site selection for on-site inspection in arms control,” *Contemporary Security Policy*, 13 (3), 1992, pp 439–462.

2. Monitoring Regimes for All-Warhead Agreements

ALEXANDER GLASER

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.

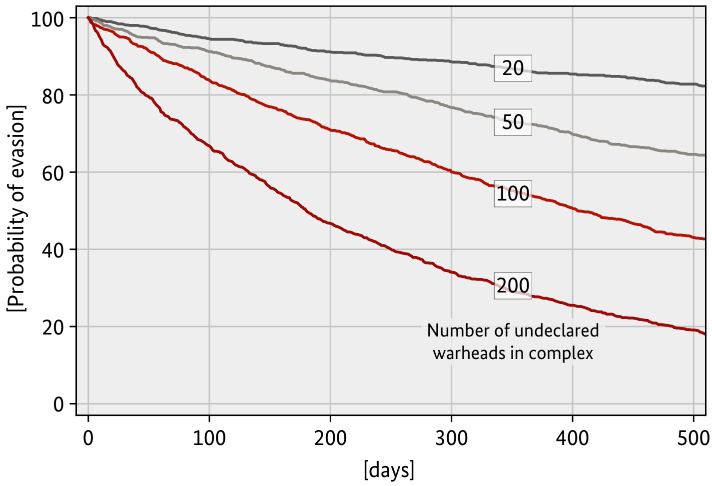
The absence regime: confirming numerical limits without access and identification

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.

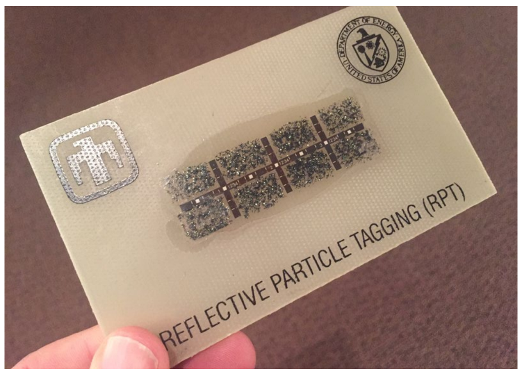
While overdeclaring the warhead inventory is not particularly problematic from the perspective of treaty compliance, underdeclaring the inventory clearly is a major concern. The question therefore arises how likely it is that undeclared treaty-accountable items can be hidden in plain sight – a scenario 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."

3. Fissile Material Stocks and Production

SHARON SQUASSONI AND MALTE GÖTTSCHE

ABSTRACT. *Fissile material is the building block of nuclear weapons and verifying production and stocks is a key step within nuclear disarmament verification. The monitoring system devised to restrict the spread of nuclear weapons (International Atomic Energy Agency nuclear material accounting and control, or safeguards) is necessary but not sufficient in a scenario of much smaller nuclear arsenals and, eventually, zero nuclear weapons. States with decades worth of production experience and stocks pose technical challenges for verification. This analysis proposes measures that can be taken now to facilitate future verification at lower arsenal levels and eventually in the context of zero nuclear weapons. They include technical national preparatory measures, transparency initiatives to build confidence, and restrictions in fissile material production, which could yield less intrusive verification requirements and ease associated challenges.*

Introduction

Interim steps to help verify fissile material should provide a foundation for and contribute to confidence in a more comprehensive verification system, whether they are incorporated into legally binding agreements or voluntary arrangements. Some seemingly small steps now can yield bigger future verification dividends. Accuracy about existing fissile material stocks will be very important, as will confidence about production processes. The chapter discusses strengthening existing measures to monitor fissile material, actions to declare, reduce, or repurpose stockpiles and those to limit fuel cycle operations or facilities as potentially useful steps to simplify verification further into the future.

Fissile material: technical scope of the problem

There are almost two thousand tons of weapons-usable fissile material in military and civilian sectors, enough for hundreds of thousands of weapons.[1] The International Panel on Fissile Materials (IPFM) estimated the 2019 global stockpile of highly enriched uranium (HEU) at 1335 metric tons and separated plutonium at about 530 metric tons.[2] Most of the HEU is now in the defense sector as a result of the global "clean-out" of HEU in the context of the nuclear security summits from 2010 to 2016. Moreover, much of the HEU designated for strategic, national security or defense purposes is likely not for nuclear weapons but rather naval or other defense reactors. For plutonium, more than half (310 tons) of the total has accumulated in the civilian sector. Roughly speaking, the most material resides in the countries that have the least monitoring, because they are nuclear weapon states not subject to mandatory monitoring under the Nuclear Non-Proliferation Treaty (NPT).

Of material in the military sectors, the United States and Russia hold the most HEU and plutonium, the result of Cold War overproduction and the dismantling of thousands of warheads. According to IPFM, the United Kingdom, France and China each have less than one-twentieth of either the United States' or Russia's stockpile.

The stockpile of fissile material ranges in its attractiveness for weapons, with weapons-grade as most attractive.[3] An eventual, comprehensive regime will need to sort out how widely to define fissile material. The more material and facilities that are captured, the more comprehensive the verification system would likely be. What might be acceptable in the context of a treaty to stop fissile material production for weapons (verifying HEU enrichment and separation of plutonium from spent nuclear fuel) would not be comprehensive enough in a nuclear disarmament regime. Technically, any form of uranium can be converted ("enriched") to weapons-grade given enough feed material and operational production equipment. Low enriched uranium (LEU) is impractical in a bomb, but excellent as feeder stock to enrich to higher, weapons-usable levels (above 90%). Although weapon-grade plutonium would be preferred, any composition can be used for warheads. This is why any verification regime must consider both stocks and production capabilities to enrich uranium or separate plutonium.

The above inventory estimates are rough independent assessments, culled from spotty government declarations. To-date, of the weapon states only the United States and the United Kingdom have made public declarations on their military fissile material inventories, which also include information on their history.

The U.S. Department of Energy issued its plutonium declaration in 1996[4] and updated it in 2012;[5] HEU holdings were declared in 2006 and updated the same year[6]. The United Kingdom made its first declaration in 1998, essentially in a single sentence: "Our current defence stocks are 7.6 tonnes of plutonium, 21.9 tonnes of highly enriched uranium and 15,000 tonnes of other forms of uranium".[7] It released somewhat more detailed declarations on historical plutonium and HEU accounting in 2000 and 2006.[8]

For these declarations, the states themselves had difficulty in reconciling physical and book inventories.[9] While the United States, for example, stated in 1996 that 1.1 tons of plutonium went to waste at its Hanford production site, a newer estimate assumes 4 tons. As of 2009, the total plutonium stock the United States manages is 2.4 tons lower than what it should possess according to its records.[10]

This quantity theoretically corresponds to hundreds of weapon-equivalents. It is not clear, however, if the material ever existed. As part of disarmament verification efforts, the balance between the physical and book inventories will need to be closed. This will require conducting nuclear archaeology, a toolset to reconstruct fissile material production histories by means of forensic measurements in shut-down facilities.[11]

In addition to stocks, the scope of the problem is affected by the number of closed and operational facilities. Five of the nine states with nuclear weapons stopped producing fissile material for weapons more than two decades ago. A verification regime would need to develop measures for facilities that are dismantled, standby and operational. Some civilian enrichment and reprocessing plants (as discussed below) are monitored but not all. The dual-use nature of much of the material means that restricting production carries costs.

Political scope of the problem

Significant political obstacles have blocked negotiations of a treaty to halt fissile material production for use in weapons (FMCT). Experts are familiar with the decades-long standoff on whether a treaty that bans fissile material production for nuclear weapons should cover existing stocks or not, rooted partly in a regional rivalry between Pakistan and India but also likely in reluctance to cede advantages in perpetuity. It was not a coincidence that the five nuclear weapon states regarded an FMCT as a nonproliferation vehicle to cap smaller arsenals. For some non-nuclear weapon states, it was important after the 1995 NPT Extension Conference to lock in real disarmament results, which meant not just codifying decisions to stop production but also drawing down stockpiles. Some countries see an FMCT as a vehicle to redress the uneven application of IAEA safeguards between non-nuclear-weapon states and nuclear weapon states under the NPT, and the uneven distribution of enrichment and reprocessing capabilities across the world.

Precedents

There is one precedent of a state with a nuclear weapons stockpile and fissile material dismantling its stockpile and placing material under IAEA safeguards, which is South Africa. While the IAEA admitted that its assessments were not free from uncertainty, inspections, sampling, and examination of records allowed the IAEA to declare that “there were no indications to suggest that the initial inventory is incomplete or that the South African nuclear weapons program had not been completely terminated and dismantled.”[12] For the purposes of this discussion, the South African model suggests that greater attention to fissile material balances in the disarmament process could possibly bridge difficulties in monitoring dismantlement of warheads.

Of note, although South Africa destroyed documentation about the weapons themselves days before IAEA inspectors arrived in 1993, it preserved thousands of pages related to HEU components and fissile material production that aided the IAEA's assessment, including reconciliation of inventory differences at the high- and low-enrichment plants. One issue was a lack of knowledge how much U-235 was in the enrichment tails. Those were eventually measured by the IAEA, a process that took several years. Inspectors eventually stated that the HEU was fully accounted for.

Special monitoring in South Africa continued until 2004, when the IAEA revisited all key sites of the program. It was only in 2010 that the IAEA drew the broader conclusion.[13] This precedent suggests that credible explanations for inventory differences will be key to enhancing confidence, but that such a process must be conducted over long periods of time. Moreover, it is likely that South Africa's small nuclear weapons program, which produced 6-7 devices and spanned 20 years, presents far fewer complications regarding nuclear forensics than the nine current nuclear weapons programs, with the possible exception of North Korea. Accounting for these programs will be significantly more complicated, costly, and intrusive.

North Korea also provides a precedent of a different sort. A key stumbling block in North Korea's accession to the NPT was uncertainty about its baseline declaration of material. A suspicion that North Korea's required initial declaration of fissile material was too low (90 grams of separated plutonium) led the IAEA to request corroborating information from waste storage sites, waste streams, and other measurements at the Yongbyon reprocessing plant. Not all of these requests were granted, but the measurements that were taken confirmed the suspicions. Nevertheless, the U.S.-North Korea Agreed Framework, which froze plutonium production for the DPRK, was successfully negotiated, effectively sweeping aside resolution of issues around the initial declaration. North Korea never fully came into compliance with its NPT obligations, yet its plutonium production program was frozen for eight years. This model demonstrates the potential for nuclear forensics in confirming or challenging fissile material declarations. Such measures could play an even greater role on the path to nuclear disarmament, particularly if states become less willing to let compliance slide in the face of political expedience.

State of Play: Monitoring Fissile Material

The International Atomic Energy Agency has been monitoring nuclear material, equipment and facilities for more than six decades and now applies nuclear safeguards in 183 countries.

For the vast majority of states under nuclear safeguards agreements, the IAEA performs both positive and negative verification – to provide confidence that declared material and facilities are used as declared (for peaceful purposes) and confidence there are no undeclared fuel cycle or other relevant facilities or activities indicting possible military dimensions. In states with nuclear weapons, it performs only positive verification – that declared items and activities are used as stated. Of course, in a scenario of nuclear disarmament, the performance of negative verification – verifying the absence of fissile material for nuclear weapons – becomes especially important.

The basics of IAEA monitoring are well-known:

- Nuclear material accountancy (also known as MPC&A, or material protection, control and accounting)
- Design information verification (of facilities)
- Environmental sampling
- Measurement techniques: item counting, weighing, non-destructive assay; destructive assay (sampling)
- Containment and surveillance (cameras; detection equipment); unattended monitoring with remote data transmission
- Satellite imagery and open-source information

States that have concluded Comprehensive Safeguards Agreements must submit initial declarations of their facilities and fissile material holdings to the IAEA. Verifying their correctness and completeness has been a complex undertaking for states that had nuclear programs prior to joining the Non-Proliferation Treaty, such as Argentina, Brazil, North Korea, Ukraine, Lithuania and Kazakhstan. In principle, the IAEA can demand historical operating records, and assess the internal consistency of the declared past, present and planned nuclear program.[14] It is not clear, however, that the IAEA systematically demands or analyzes information about a state's past nuclear activities. It builds confidence over time as safeguards are being applied in a routinely manner, if no suspicions arise.

Most countries under comprehensive safeguards agreements do not pose a significant risk of diverting fissile material for weapons – they neither have stocks of weapons-usable fissile material nor the facilities to enrich uranium or separate plutonium. Once countries acquire sensitive fuel cycle facilities, the risks escalate. The IAEA responded to such proliferation risks in Iraq in 1991 and North Korea in 1992 by adding new technical measures and authorities to its safeguards regime via the Additional Protocol.[15]

The case of Iran, however, is perhaps even more instructive. In addition to implementing the Additional Protocol, parties to the Joint Comprehensive Plan of Action (JCPOA) felt it necessary to ensure that Iran's breakout time – time to produce a nuclear weapon – was lengthened to at least one year by restricting both material stockpiles and production capabilities. Limits on LEU stockpiles, on the sophistication and numbers of uranium enrichment centrifuges (limiting their individual separation capabilities), and the number of facilities, and even monitoring of centrifuge assembly and procurement activities are part of the JCPOA. At the Natanz enrichment facility, on-line enrichment monitoring, which provides real-time data about enrichment levels, and therefore improves timeliness, was also installed.[16]

Monitoring in states with nuclear weapons

Except for North Korea, all states with nuclear weapons currently have some monitoring of fissile material stocks and production, whether they are party to the NPT or not (India, Pakistan and Israel). As might be expected, these are mostly confined to the civilian sector and even then, applied to just a fraction of their entire nuclear energy assets. Within the NPT, Russia, China, the United States, France, and the United Kingdom have Voluntary Offer Agreements. Each country submits a list of eligible facilities and material to be safeguarded by the IAEA and the IAEA chooses, on an annual basis, whether or not to apply safeguards. The state determines the list of eligible facilities and is also able to withdraw any facilities from that list for national security reasons (using a national security exclusion clause).

According to the Safeguards Implementation Report 2019, China had three facilities under safeguards (one power reactor, one research reactor and one enrichment plant); the United States and Russia each had one storage facility under safeguards; France had one enrichment, one reprocessing and one fuel fabrication plant under safeguards; and the United Kingdom had one enrichment and two storage facilities under safeguards.[17] France's commercial uranium enrichment and reprocessing facilities are safeguarded by EURATOM and the IAEA.[18] Of the states with nuclear weapons, six have an Additional Protocol in force – the United States, United Kingdom, Russia, China, France and India – and all have significant national security exclusions therein. However, the expense of applying safeguards to large industrial-scale facilities when diversion to nuclear weapons is not a risk has meant that little monitoring occurs in practice.

Outside of the NPT, India, Pakistan and Israel have a few material- or facility-specific INFCIRC/66-type agreements and no monitoring at all of weapons-related material or production. Pakistan has seven power reactors under safeguards and two research reactors; India has 10 power reactors (half of its total), two fuel fabrication and two storage sites under IAEA safeguards; Israel has one research reactor under safeguards. Only North Korea has had some monitoring of its military plutonium production facilities at Yongbyon when shut down, but no monitoring of its HEU production. Since North Korea pulled out of the NPT in January 2003, IAEA verification has been sporadic, limited to a few visits in 2007 and 2008 to confirm the shutdown of the Yongbyon reactor and reprocessing plant.

India, Pakistan and North Korea continue to produce fissile material for nuclear weapons at unsafeguarded facilities. France, Russia, and India operate civilian reprocessing plants (the United Kingdom's and Japan's plants are not operating at the moment) to separate plutonium from spent nuclear power reactor fuel. These are not all under IAEA safeguards. China has a pilot civilian reprocessing facility but plans to open a larger, industrial-scale plant have been on hold for several years.[19] All states with nuclear weapons, except for Israel, have uranium enrichment facilities, both civilian and military plants, with some of the civilian plants (in United Kingdom, France, and China) under or having been under EURATOM or IAEA safeguards.[20] In several states, there are plants that are no longer operational, both for military and civilian purposes. A comprehensive verification regime would likely seek to verify that these plants were shutdown, nonoperational, repurposed or dismantled.

The line between civilian and military material and production is not always as clear as one might expect. Some states with nuclear weapons have defined material as strategic or of national security importance, raising the question of whether it will be used for defense purposes other than weapons. Exclusions of material for national security purposes – but not nuclear weapons – could raise verification complications in the future. An analog exists in comprehensive safeguards agreements (paragraph 14 of INFCIRC/153) but has not yet been tested.[21] These kinds of exclusions would need to be addressed in any comprehensive nuclear disarmament verification regime.

Steps like declaring weapons material excess to defense needs can help in creating more transparency. So far, the United States, Russia and the United Kingdom have made declarations.[22] Some of this material is safeguarded: The United Kingdom declared 0.3 tons of plutonium as excess in 1998 and put it under IAEA safeguards.[23] The United States has a little less than three tons of plutonium placed under IAEA safeguards at the K-Area Material Storage (KAMS) at the Savannah River Site.[24] The development of international guidelines to manage plutonium stockpiles was another helpful step in transparency, although the voluntary reporting scheme that became INFCIRC/549 in the late 1990s never really developed into a management mechanism.

Challenges specific to nuclear weapon states

Verifying fissile material stocks, production, or the absence thereof in states that have or had nuclear weapons will be difficult for several technical and political reasons. For example, the lack of material accountancy history or equipment (e.g., calibration in tanks, etc.) in production facilities can complicate verification, as could an abundance of isotope signatures from past production. Yet, developing an entirely new system of verification for nuclear weapon states' fissile material could raise suspicions that the existing NPT material accountancy system is either too strict or too lenient. A hybrid approach is likely to emerge that builds upon the NPT safeguards system but adds aspects tailored to weapon states.

Some questions to consider in designing verification for states that have manufactured nuclear weapons include:

Verifying fissile material production

- How to cope with older, existing bulk handling facilities in terms of design verification and MPC&A?
- Are existing standards of timeliness and significant quantities appropriate and achievable for such states?
- How can sensitive/classified information be protected when inspecting production facilities? Specifically, can environmental sampling be tailored accordingly? Is there a role for containment/surveillance at sensitive sites?

Verifying fissile material inventories

- What level of uncertainty is acceptable and allowable in verifying fissile material inventories?
- Can provisions for managed access designed in other contexts (JCPOA, Chemical Weapons Convention, etc.) be adapted to fissile material verification?
- How to handle the transition from fissile materials currently in weapons to stocks?
- What is adequate and achievable monitoring for fissile material used in non-explosive military purposes (e.g., naval fuel and other uses)? If none, should these uses be restricted?

Preparing for Verifying Production Facilities

The table below arrays the various verification tasks according to type of facility encountered. It identifies approaches and the availability of certain technologies as well as some of the challenges. Broadly, the IAEA has learned over time that the more information it has about how a facility is designed and operated, the greater confidence it has that it would be able to detect undeclared activities like diversion of material or diversion of processes to produce undeclared material. States with CSAs are now required to inform the Agency as they are planning facilities, rather than when nuclear material is introduced to the site. Of course, states with nuclear weapons present the ultimate challenge to this because they have had full-fledged operating facilities for many years.

	Disabled or shut-down facilities	**Operational enrichment/reprocessing** *a. with restrictions* *b. without restrictions*
No diversion		MPC&A* *Tougher in plants not designed for safeguards, or without restrictions*
No undeclared production at declared facilities	Verify non-operational status at key points; remote monitoring*; satellite imagery* and standoff detection** (e.g. Kr-85)	MPC&A; unattended monitoring; detecting HEU production if prohibited: evironmental sampling suffcient; *greater timeliness and accounting gaps without restrictions*
No undeclared facilities/sites	Open-source information*; National Technical Means (NTM)*	Open-source information; NTM*; MPC&A in declared facilities up-stream to detect undeclared facilities down-stream; challenge inspections incl. environmental sampling*; wide-area environmental sampling** (reprocessing up to some distance, impossible for centrifuge plants)

Verification Tasks at Possible Production Sites. This table focuses on enrichment/reprocessing, but verification could include conversion, fuel fabrication, reactors and spent fuel storage.
* = Readily available; ** Limited availability

National preparatory measures

Nuclear weapon states could bypass the requirement for complex verification measures by decommissioning and dismantling production facilities. Or, they could choose to convert older facilities for peaceful fissile material production with safeguards in mind.[25] In some cases, facilities may already be producing for civilian uses but are not safeguarded.

They should begin to address technical questions around the application of safeguards to their large bulk handling facilities (fuel fabrication, uranium enrichment and spent fuel reprocessing plants). In some cases, they will need to reconcile their state systems of accounting and control (SSACs) with IAEA safeguards. In new facilities, safeguards can be designed into the process.

Information, such as it is, should start to be collected on the design of facilities that might continue to operate into the future to aid initial design verification tasks. Knowledge gained from interviewing personnel who understand the processes, although perhaps now classified, could be saved for a later date to help provide important context.

Even in states without nuclear weapons, meeting detection thresholds at large bulk-handling facilities is difficult. It is therefore reasonable to inquire whether the current detection thresholds (in terms of timeliness and significant quantities of material) are relevant to states that already have nuclear weapons.[26] Existing uranium enrichment, fuel fabrication or reprocessing facilities not currently under safeguards that continue operating under a future nuclear disarmament verification regime would pose particular challenges. *Preserving information on past material unaccounted for (MUF) could be helpful later to establish its continuity over time.*

Easing verification by limiting the fuel cycle

One approach to the problem of timeliness in the context of nonproliferation is to multilateralize enrichment and reprocessing facilities. The idea is that with international management or ownership of a facility, there would be much greater transparency and therefore earlier warning (or deterrence) of misuse of such facilities. Institutional approaches to the specific risks posed by enrichment and reprocessing facilities are not verification solutions, but rather a frame that could potentially support verification tools.[27] Internationalizing all fuel cycle activities has been proposed episodically in the past (every thirty years from the 1940s), usually with the caveat that it is politically difficult or unappealing because of limits on sovereignty. Suppliers have relied therefore primarily on limiting the spread of enrichment and reprocessing through harmonized export controls within the Nuclear Suppliers Group established in 1974.

With respect to the specific technical challenges that large bulk-handling facilities pose because they "lose" materials in-process that, while statistically acceptable, amount to several bombs' worth of fissile material, one could expect greater intrusiveness in the form of permanently stationed inspectors, remote monitoring and local and wide-area environmental sampling to provide desired confidence. Like proposals to internationalize the fuel cycle, proposals to limit operations, such as halting production altogether or restricting production in terms of quantities, operating protocols (limiting working stocks, for example, at reprocessing plants), or locations, have been viewed as unacceptable limits on sovereignty and therefore unpopular. As measures to simplify more comprehensive verification tasks, however, they could gain political traction. These are, again, not verification measures, but could simplify some of the tasks. For instance, if enrichment was limited to LEU only, location-specific environmental sampling could verify the non-production of HEU, eliminating the need for HEU material accounting.[28]

Technical verification measures

Perhaps the easiest verification challenge along the path towards disarmament is verifying facilities that are no longer operating, in whatever stage of decommissioning they are in. The IAEA has significant experience in monitoring non-operating facilities. However, its approaches were developed with an assumption of continuity in safeguards as a facility moves from operational to shut-down status.

A facility's non-operational status can be verified by confirming the removal of key equipment (feed/withdrawal areas in enrichment plants; head-end/dissolver equipment at reprocessing plants) as well as containment and surveillance measures, including monitoring waste streams and/or storage. Dismantlement of facilities would also likely require intrusive on-site visits, but destruction of facilities can be verified via remote monitoring (satellite imagery). Once confirmed, remote monitoring can verify the absence of changes. In facilities that have been cleaned out and dismantled, it should be relatively easy to confirm the absence of newly processed fissile material.

Location-specific environmental sampling can not only be helpful to verify that declared facilities have not been recently used for fissile material production, but also to confirm whether suspected undeclared sites have been used for this purpose. Environmental sampling has been a powerful technique deployed by the IAEA since the mid-1990s (see chapter on *Nuclear Monitoring and Verification Without Onsite Access* in this report). Similar methods are used in nuclear forensics. In the case of reprocessing, it is possible to determine roughly when fission products have last been separated from plutonium or uranium in sampled material because the decay products are predictable.[29] In the case of enrichment, it may under specific circumstances be possible to detect the age of HEU particles.[30] This would also be helpful to verify the absence of HEU production in facilities that should only produce LEU, but may have produced HEU in the past when this had not been regulated.

A key concern of states with nuclear weapons will be protecting sensitive information for national security, nonproliferation, and commercial proprietary reasons. In a zero nuclear weapons scenario, some national security barriers will no longer exist, but nonproliferation will continue to be a concern. In states with nuclear weapons, the use of environmental sampling could reveal sensitive information not specifically limited to fissile material or yield false positives because of the abundance of weapons-grade material particles at a variety of production and non-production sites.

States could develop a library of local environmental samples, or at the very least, put together an environmental sampling protocol that factors in any potential sensitivities at sites. Operators could begin collecting data that summarizes their experiences at specific facilities, with the aim of sharing experiences to support verification in the future.

Managed access to shield information from inspectors that could be considered sensitive is a feature of the Chemical Weapons Convention (CWC) for chemical production facilities. Procedures like removing papers from office areas, shrouding sensitive displays, stores, equipment, turning off computers, restricting sample analysis and randomizing access were detailed in the treaty itself. In the fissile material world, limited frequency, unannounced access inspections for enrichment plants producing 5% U-235 or less were devised under the Hexapartite Safeguards Project in 1980. More recently, facility operators at safeguarded enrichment facilities in Brazil were able to shroud centrifuges to protect proprietary information.[31] For states with nuclear weapons unused to foreign inspectors, managed access is likely to play a role, both at declared facilities and undeclared sites. The specific procedural details for so-called challenge inspections included in the JCPOA could also be adopted to support other technical verification measures.

Finally, containment and surveillance technologies play a key role in safeguards implementation. For some states with nuclear weapons, production facilities may be located near or at sensitive military sites, which could complicate introduction of these kinds of safeguards measures. The easiest solution would be to shut down such facilities, but then again, some sporadic access or monitoring to ensure no undeclared activities would still be required.

Preparing for Verifying Stocks

Compared to IAEA safeguards today, the challenge of verifying fissile materials in weapon states is that large amounts of stocks are stored at sensitive sites and contain sensitive characteristics. These include fissile material currently in weapons, stocks available for weapons and to some extent stocks declared excess to weapon needs, as well as weapons-usable material in naval propulsion programs.

Technical verification and national preparatory measures

While fissile material baseline declarations could be verified with material accountancy measures, this would be extraordinarily intrusive. Instead, verification could begin by conducting nuclear archaeology, which does not require direct access to the materials and may therefore be less intrusive.

Similar to what the IAEA has done in North Korea and South Africa following their initial declarations, nuclear archaeology aims at reconstructing the fissile material production and removal history to quantify which stocks should exist today. Experts and states should develop a toolbox systematically, examining how documentation of the past fissile material production and removals (e.g. lost to waste, used in weapon tests) can be analyzed efficiently, and how forensic measurements in shut-down fuel cycle facilities and of produced waste can contribute.

To ensure that documentation will remain accessible, weapon states could initiate an effort to consolidate their document collections (hardcopy and digital) relating to the fissile material and fuel cycle history. Key personnel involved in the program should be involved and interviewed to ensure their knowledge is being documented.

The facilities should be preserved to the extent possible. If they are nevertheless dismantled, samples that may be used for nuclear archaeology purposes should be retained.[32]

Weapon states should re-examine own fissile material production and losses. While some states – most notably the United States – have engaged in nuclear archaeology research, its methods are not mentioned in any fissile material declarations or reports, and therefore have likely not been used more widely yet. Undertaking a process of fully characterizing and accounting for nuclear materials by applying nuclear archaeology methods would create nuclear security and safety benefits. Furthermore, it would provide a better basis for a future situation when fissile material stocks will be verified.

Parallel to conducting nuclear archaeology in the future, the amount of fissile materials that are part of a regime including on-site inspections can be gradually increased. It can begin with materials in the civilian cycle, and those materials declared excess to weapons needs that are no longer considered sensitive. Declared fissile materials with sensitive characteristics could be verified using containment and surveillance measures, initially without characterizing them. Experts should examine how such measures could be implemented at sensitive sites, where inspector access must be managed.[33]

Eventually, measurements of such sensitive items could be performed by shrouding characteristics considered sensitive, for example, by using information barriers. At some point, however, as part of nuclear disarmament, all fissile materials from the weapons sector will need to be put under safeguards, either as they are being converted to civilian use, or as they are disposed of.

A particular challenge is assessing the mass of the fissile materials resulting from dismantled warheads or other sensitive items related to the weapons program, because the amount of fissile material contained in individual warheads is usually considered classified. One option: The material from weapons could be blended with other fissile material stocks, before allowing inspectors to measure the total mass. Another option would be to dispose of the fissile materials from weapons by gradually removing the stocks stored after dismantlement and converting them to items of standard masses before inspectors could measure them. If the amount of fissile materials remaining in the storage area could not be measured by inspectors, the mass per warhead would not be revealed. Average warhead masses could only be deduced once most fissile materials from the storage area have been removed. By then, assuming global zero were at least close, this information might not be considered that sensitive anymore.[34]

Assuming verification of all other fissile materials (including naval fuel), as dismantlement progresses, a state would move towards placing all fissile materials under safeguards. Inspectors would compare the quantity of fissile materials under safeguards to the amount of fissile materials a state should possess according to nuclear archaeology. As nuclear disarmament progresses, one moves towards "closing the fissile material balance". [35] The inspections in South Africa are an example of this and show that the international community requires such an effort to be confident that a state has fully disarmed.

Verifying weapons-usable materials in naval propulsion programs may, however, be the biggest challenge. A state may divert material from naval programs to weapons purposes, speculating it will remain undetected. It may even under-declare naval stocks for this purpose. For naval programs, there is no IAEA safeguards experience to draw on. Direct access to fuel is considered especially intrusive because the geometry of fuel element is considered sensitive, so no direct measurements are possible. Also, naval fuel cycles are typically spread across a larger number of locations, which limits the applicability of perimeter monitoring.

While promising approaches based on continuity of knowledge and limited measurements exist, they would require a significant level of inspector access, including when fuel from submarines is being removed or installed.[36] *States should examine how such approaches could in principle be implemented in their enterprises.* From a verification perspective, requiring all naval propulsion to use only LEU fuel raises the costs and reduces the risks of diversion of material declared in the naval fuel cycle.[37]

Interim Steps: Transparency and Limitations

As states with nuclear weapons have little monitoring currently on their activities in either military or civilian sectors, there is ample room for technical monitoring measures should the requisite political will materialize.[38] However, transparency (and willingness to engage in transparency) varies greatly among the nine. In a state of zero nuclear weapons, all countries will have the same obligations. Until that point, however, significant differences will remain. It may not be possible to apply technical measures across the board, but rather provide a menu of options that can improve technical baselines for future monitoring.

Measures for production facilities

Safeguarding civilian facilities in NPT states. Nuclear weapon states are not required to place enrichment and reprocessing plants under IAEA safeguards and even when they make the facilities eligible (like the United States does), the IAEA has not chosen to inspect them for reasons of cost.[39] All states with Voluntary Offer Agreements should request the IAEA to safeguard their commercial enrichment and reprocessing plants and provide the funding for inspections. For states outside the NPT, they should similarly commit to placing more civilian facilities under safeguards, particularly enrichment and reprocessing but also fuel fabrication plants, where material flows are significant.

Transparency regarding former military production facilities. Given that any comprehensive verification regime will likely seek to provide assurances that former military production facilities continue in that status, states with shutdown facilities should jointly consider ways to document processes and monitor shutdown. The examples of the Pierrelatte gaseous diffusion plant and K-25 in the United States, and the Eurochemic reprocessing plant all provide models for thorough documentation of their dismantlement and decontamination processes.[40]

Technical working group to discuss monitoring. Developing technologies specifically for facilities in states with nuclear weapons that are not now safeguarded but could be safeguarded in the future could be a multinational endeavor. For instance, a technical working group could be founded for this purpose. In some cases, there may be synergies with technical safety measures. For example, a specially designed gamma volumetric analyzer apparatus that quantified the U-235 inside each diffuser at Pierrelatte before disassembly was used to ensure that quantities did not exceed criticality thresholds when barrier material from the gaseous diffusion material was mixed together before being crushed.[41]

Transparency regarding military production facilities in non-NPT states. India, Pakistan, DPRK and Israel have not declared moratoria on fissile material production for nuclear weapons. They can be presumed to continue such production. As long as they are producing such material, they will reject most measures to provide additional transparency. They could, however, declare the locations, size and technology of such plants as a starting point to build a baseline. It may be feasible for India, Pakistan and at some point DPRK. Many experts, however, presume that Israel would prefer to close down any military production facilities rather than have to declare it had a military program, given its historical opacity regarding its nuclear deterrent.

The case of plutonium in Japan

Japan is one of four countries reporting under INFCIRC/549 with purely civilian stockpiles of separated plutonium – 9 metric tons at home and 36.6 metric tons in the United Kingdom and France. Prior to 2018, industry committed to balancing supply with demand, and the government stated it would not hold plutonium without a purpose. These measures did not stop stockpile growth, however, and in 2018, Japanese officials finally stated that stockpiles needed to be reduced.

With its plutonium utilization program completely upset by the 2011 accident at Fukushima, which shut down the majority of its nuclear power reactors, there is ample plutonium to provide mixed oxide (Pu-U) fuel for many years. Currently, twenty-seven reactors are under licensing evaluation for burning mixed oxide fuel using plutonium; ten may be licensed for MOX operation. Four reactors that now utilize MOX fuel may have to be shut down. The Rokkasho Reprocessing Plant anticipates reopening in 2023 after safety modifications.

In 2018, Japan specified a process to reduce its plutonium stockpile. New regulations allow the government to control reprocessing and each year, a committee has to submit a plan for reprocessing for approval. New rules also encourage one utility company to borrow plutonium from another, thereby reducing the demand for reprocessing.

Limiting civilian enrichment and reprocessing, including operational limits. Steps that minimize plutonium production could build transparency and confidence. For example, entities conducting reprocessing could commit to drawing down stocks of separated plutonium before embarking on additional reprocessing campaigns (compare to the case of plutonium in Japan, see textbox). This, and other measures like plutonium-use plans, could be particularly important in nuclear weapon states that conduct civilian reprocessing to improve transparency for future verification efforts. Voluntary limits on uranium stocks, particularly in conjunction with international fuel banks, could provide transparency given the lack of any restrictions on stockpiles in the NPT. More far-reaching proposals such as a moratorium on new enrichment and reprocessing plants, phasing out HEU production and reprocessing altogether, or requiring any new enrichment or reprocessing plant to have multinational ownership or management, have been considered without much enthusiasm or entirely discarded in the context of nonproliferation. Some variation on this theme may be more attractive as features on the path toward nuclear disarmament.

Operational restrictions might be considered less radical. For example, governments could agree to license enrichment permits at 6% U-235 or below and facilitate voluntary installation of on-line enrichment monitors so that they become standard equipment. Some operational restrictions could make future verification tasks simpler, less intrusive, and potentially less costly.

Measures for inventories

As the South Africa precedent case has shown, building confidence in the correctness and completeness of fissile material declarations takes a long time – and South Africa's weapons program was relatively small. The problem begins with weapon states themselves having difficulties reconciling their book inventories with actual fissile material stocks. Furthermore, no single verification measure can provide confidence that a state will not deliberately withhold undeclared stocks. By increasing transparency and examining technical measures, this confidence-building process should begin now.

International exercises to develop verification approaches. Apart from the existing detailed United States and United Kingdom as well as the INFCIRC/549 declarations, nuclear weapon states currently do not provide much transparency into fissile material inventories. There are, however, options for transparency and confidence-building related to nuclear archaeology, which do not require issuing new declarations on fissile material inventories.[42] For example, an international exercise to share methodologies for reconstructing fissile material inventories could be held. Such an exercise need not even be held in a nuclear weapon state. Some civilian programs share technical characteristics with military programs. Some selected documentation from past operations could be used as a basis to discuss how to reconstruct how much fissile material has been produced. In such a framing, nuclear weapon states can freely decide which information they are ready to share about their process of examining their inventories. Topics could include how to deal with classification issues and loss of continuity in data. With an appropriate level of confidence among participants, an exercise to discuss nuclear archaeology methods could be held in a nuclear weapon state. The weapon state would provide some data from its program, that it is ready to share.

Inspection visits in one or more facilities. Moving from exercises to implementation, an inspection could be carried out to assess a specified part of an existing declaration, in particular in the United States or in the United Kingdom It could directly build confidence in the correctness of the declaration(s). It can be limited in scope, such as containing operational records of only one nuclear facility covering a period of one or two years. The United States has already released the amount of plutonium produced per site per year, along with some additional information regarding the operation of facilities such as the power levels of the reactors. The United Kingdom has declared information on plutonium transfers from the reprocessing facility in Sellafield to the weapons program in Aldermaston, also per year. Only examining one or a few years would prevent inferring independent knowledge about the total inventory, which would likely be considered too intrusive at this point.

Update existing declarations. The fissile material declarations of the United States and the United Kingdom are now roughly a decade old. The two states could update their existing declarations, in order to encourage other states that have not yet done so to also declare information on fissile material inventories. Unfortunately, the United Kingdom announced in its Integrated Review in March 2021 that it will reduce transparency about its nuclear arsenal, making progress on fissile material transparency unlikely.

Reinvigorate INFCIRC/549 declarations. With so little information about even civilian enrichment and reprocessing in the public domain, efforts to reinvigorate existing reporting mechanisms like INFCIRC/549 could be useful. INFCIRC/549 could serve as a vehicle for reporting on material declared excess to defense needs and adherents could consider whether to add monitoring measures to those declarations. Improved HEU reporting could be helpful for efforts to minimize the use of HEU in the civil sector and in the context of a future treaty to eliminate fissile material production for weapons. Finally, promoting information exchange is one of a dozen measures identified in INFCIRC/869 as contributing to strengthened nuclear security implementation. In preparation for an eventual comprehensive regime, bringing along countries like India, Pakistan, Israel and North Korea into the guidelines would be useful.

Declare additional material excess to defense needs. States should consider whether they can declare additional fissile materials as excess to defense needs, and place more of that under safeguards – to the extent it no longer has classified characteristics. Since the United States and the United Kingdom put such material under safeguards, they and other states have continued dismantling warheads, and have large military stocks that are not in weapons. Therefore, there would be room to indicate or increase the amount of excess stocks. Unfortunately, the United Kingdom's Integrated Review in March 2021, which stated that the United Kingdom would increase its stockpile ceiling to 260 warheads rather than reduce down to 180 warheads, suggests it is unlikely that the United Kingdom will declare further material in excess of defense needs.

From Reductions to Verifying After Disarmament: Toward Constructing an Airtight Regime?

From a practical perspective, placing all enrichment and reprocessing facilities under IAEA safeguards is effectively a halt in the production of fissile material for weapons.[43] A treaty is not necessary except to make progress irreversible or to specifically address stocks, which are not limited in any way by the NPT. In the past, experts have proposed keeping a fissile material treaty focused on ending production, while addressing stocks in a separate, voluntary initiative because of the deadlock in the Conference on Disarmament on an FMCT, as well as the obvious disparities in stockpile levels among states with nuclear weapons.[44]

In 2015, a Group of Governmental Experts addressed modalities of a fissile material treaty, including verification, which was followed by a High Level Group of FMCT Experts Preparatory Group report in 2018.[45] Neither set of discussions considered the role of fissile material verification at low levels of warheads or even down to zero.

While some states retain large numbers of nuclear warheads, certain gaps in the verification system may be tolerable. However, at lower warhead numbers, the need to assess the potential to build new warheads from newly produced or existing fissile materials will grow. Verified declarations will likely be required from a stability perspective: As long as nuclear weapon states subscribe to deterrence theory, it is important that strategic stability is maintained as nuclear forces are reduced to lower levels.[46]

Without reliable verification, a state could under-declare its available fissile material inventory, allowing it to suddenly emerge with a qualitative military advantage when it chooses to.[47] Given that a moderately sophisticated nuclear device could contain as little as 3-4 kilograms of plutonium or 12-15 kilograms of highly enriched uranium, speculations about undeclared fissile material stockpiles or production capacities could make arms control very difficult.

To be prepared once arriving at low numbers, developing verification methods fit for purpose, gaining experience with them, and building up confidence by phasing in such measures will be key. It may take many years until inspecting entities will have a reliable understanding of a weapon state's past and current program and will have built up confidence in a state's declarations by resolving any inconsistencies that may arise over time.

After all warheads have been dismantled, the non-diversion of fissile materials for weapons purposes will be key. The existing fissile material control regime, such as it is, was designed to inhibit proliferation by states without experience in building nuclear weapons. Rather than making it impossible to proliferate, the system makes proliferation more difficult, costlier, and easier to detect, all with the aim of deterring potential proliferators.

After disarmament, on the one hand, the risk that any state could cross the nuclear threshold would be seen as more significant to the former nuclear weapon states because reconstitution could be faster. On the other hand, nuclear weapon states might bank on reconstituting their capabilities and therefore could agree to much less stringent verification. However, it is not clear that there is a significant military advantage to be gained from just a handful of nuclear weapons, as Steve Fetter and Ivan Oelrich have argued.[48]

In any case, as long as we do not know what the world at Zero will look like, verification regimes should be developed that can provide high confidence of detecting noncompliance with sufficient time for a response. The current fissile material control regime is a starting point to be tailored for challenges inherent to monitoring in different scenarios.

In the most stringent scenario for example, seeking to accomplish the same safeguards objectives for states that formerly had nuclear weapons might require considering a wider group of materials (to include neptunium and americium); smaller thresholds for significant quantities; and shorter detection goals. Those three additions would likely increase the intrusiveness of safeguards implementation through both broader and more intense scrutiny.

The table below shows four approaches that seek to reduce risk that fissile materials are used for weapons, ranging from most to least comprehensive. The more comprehensive the approach, the less intense or intrusive verification might need to be, significantly easing associated challenges.

At the furthest end of the spectrum, the maximalist approach envisions eliminating fissile material stocks and production of fissile material entirely. This would mean a transformation of nuclear energy from fission to nuclear fusion, which does not use fissile material, or phasing out of nuclear energy entirely. However, nuclear fusion reactors still hold the potential for proliferation risk, so this scenario is not airtight.[49] One potential way to limit proliferation risks is to have a limited number of fission reactors under international control to produce an international stockpile of tritium for deuterium-tritium reactors needed for nuclear fusion.

A less drastic approach would still eliminate stocks but not all production facilities. Such facilities would all have to be under international safeguards and to add assurances, would need to shift from national ownership to multinational or international ownership and management. The elimination of sovereign control would be quite intrusive for countries that now run enrichment and reprocessing plants outside of safeguards.

A moderate approach would reduce stocks of fissile material (perhaps allowing for military non-explosive purposes) and allow for reprocessing and enrichment but not at weapons-usable levels. Alternatively, reprocessing could be phased out, as any plutonium is weapons-usable. The minimalist approach would simply have as a goal to keep stocks of weapons-usable fissile material from growing. Such stocks would be monitored as would production facilities.

Approach	Objective I: Reduce risk that fissile materials are used for weapons	Objective II: Simplify verification requirements*
Maximalist	Eliminate stocks + all fissile material production	Verification simplified to ensuring absence of stocks & verifying non-operation of facilities
Stringent	Eliminate stocks and national enrichment/reprocessing	Verification simplified to verifying non-operation of national facilities and monitoring multinational facilities
Moderate**	Reduce stocks and freeze HEU production, or alternatively also reprocessing	Detecting HEU production simplified to using location-specific environmental sampling; must continue on-site inspections and containment/surveillance to monitor reduced amounts of existing stocks; must in the first case continue to safeguard plutonium separation using process monitoring and on-site inspections
Minimalist (South Africa)	Keep stocks of weapons-usable fissile material from growing	Little simplification in verification

Approaches for reducing risk of future fissile material production while simplifying verification. * Assumes that additional verification measures for confidence in the absence of undeclared facilities and materials are established and maintained. ** A variation on this theme is the JCPOA, which eliminates reprocessing but allows LEU enrichment.

Conclusions

Fissile material is the building block of nuclear weapons and verifying production and stocks is a key step within nuclear disarmament verification. While there has been a monitoring system in place for states with just civil, peaceful nuclear energy programs, future verification in weapon states will pose unprecedented challenges: the material accounting and control system devised to restrict the spread of nuclear weapons is necessary but not sufficient in a scenario of much smaller nuclear arsenals and, eventually, zero nuclear weapons. Simply put, states with decades worth of production experience and stocks pose additional risks that will require mitigation.

Significant verification challenges will need to be overcome. Production facilities in weapon states have not been designed with safeguards in mind, and due to the lack of verification experience in those facilities, with perhaps design information being incomplete, gaining confidence in non-diversion will be challenging. Furthermore, the inspectorate must have an accurate understanding of the fissile material inventories, requiring consistency between the physical inventory and the documented production history. However, even weapon states themselves have problems reconciling those. In terms of weapon-equivalents, large uncertainties remain.

If nothing is undertaken well before reaching smaller nuclear arsenals, verification will likely need to be extraordinarily intrusive, intense, complex and costly. It will take a long time before sufficient confidence in the correctness and completeness of declarations will have been established, if possible at all.

Three types of measures can help mitigate these challenges and should be implemented as soon as feasible: national preparatory measures, transparency initiatives and restrictions in fissile material production. As part of the first, states with nuclear weapons should begin to collect data that will help address the inevitable uncertainties that will arise in older production plants not necessarily designed for material accounting, including on facility designs. They should also consolidate their document collections and interview key personnel relating to the fissile material and fuel cycle history. States should begin now to think about how preserving former production facilities, information from them or relevant items could assist in later verification tasks.

Transparency initiatives aim at building confidence already on the way to more comprehensive verification measures. NPT-weapon-states could choose from a menu, which includes placing all enrichment and reprocessing plants on eligibility lists under IAEA Voluntary Offer Agreements, issuing or updating existing fissile material declarations, reinvigorating INFCIRC/549 declarations, and declaring fissile materials excess to defense needs. Non-NPT states could at least declare the locations, size and technology of their production plants. States should establish international working groups to consider ways to verify the status of current and former production facilities and develop related monitoring technologies. Such groups should also conduct exercises to develop verification approaches to assess the correctness and completeness of fissile material inventories. All states that participate in a fissile material treaty need to explore whether existing IAEA standards of accounting will be appropriate and if not, what might replace them. Significant questions about handling the transition from fissile materials in weapons to fissile material stocks must be addressed.

Lastly, restrictions in fissile material production may help in simplifying verification tasks, particularly those that involve very intense monitoring. Restrictions on the kinds of material produced in the future and the accumulation of stocks could help minimize intrusive verification, as could internationalizing the fuel cycle. Simple approaches like limiting stockpiles could reduce inspection days at plants and simplify detection. In the past, restrictions on fuel cycle capabilities or operations have been unpopular because they have been suggested as remedies to reduce risks of proliferation and therefore applied to non-nuclear-weapon states. As measures to help build confidence, transparency, and pave the path to disarmament, such restrictions might be viewed more favorably in the future.

Endnotes

1 This chapter uses "fissile material" more generally to describe material that could be subject to verification in a nuclear disarmament regime. Its use in this chapter is almost synonymous with the definition of special fissionable material per Article XX of the IAEA statute, which states that "the term "special fissionable material" means plutonium-239; uranium-233; uranium enriched in the isotopes 235 or 233; any material "containing one or more of the foregoing; and such other fissionable material as the Board of Governors shall from time to time determine; but the term "special fissionable material" does not include source material. However, we differentiate between low-enriched uranium (up to 20% enriched in U-235) and highly enriched uranium (above 20% enriched in U-235), whereas the IAEA's special fissionable material covers all levels of enrichment. There are other isotopes of fissile material (neptunium and americium) from which nuclear weapons can be made; the IAEA has considered these but not decided to include them in its definition of special fissionable material. Since nuclear weapon states have experience with these other fissile isotopes, any future verification regime might consider including these in defining fissile material. Np-237 is a byproduct of uranium irradiation and the U.S. Department of Energy stated in 1992 that it could be used in a weapon. See, for example, R. Sanchez, D. Loaiza, R. Kimpland, D. Hayes, C. Cappiello and M. Chadwick, "Criticality of a 237Np Sphere," *Nuclear Science and Engineering*, 158:1, 2008, pp. 1-14. Americium-241 and -242 are also fissile isotopes with relatively small critical masses.

2 See International Panel on Fissile Materials estimates, Available: *http://fissilematerials.org/*.
HEU is defined as 20% U-235 or higher; separated plutonium includes mixed-oxide fuel (MOX), which is separated from fission products but not from uranium.

3 In the context of official discussions around a treaty to ban fissile material production for weapons, some countries have proposed a variety of definitions regarding the material to be captured. In particular, there have been efforts to exclude any so-called reactor-grade plutonium that contains less than 80 or 90% Pu-239.

4 *Plutonium: The First 50 Years*, U.S. Department of Energy, 1996. Available: *www.ipfmlibrary.org/doe96.pdf*.

5 *The United States Plutonium Balance, 1944-2009*, U.S. Department of Energy, 2012. Available: *www.ipfmlibrary.org/doe12.pdf*.

6 *Highly Enriched Uranium: Striking a Balance (Revision 1)*, U.S. Department of Energy, 2001. Available: *www.ipfmlibrary.org/doe01.pdf*.
Highly Enriched Uranium Inventory: Amounts of Highly Enriched Uranium in the United States, U.S. Department of Energy, 2006. Available: *www.ipfmlibrary.org/doe06f.pdf*.

7 *Strategic Defence Review: Modern Forces for the Modern World*, U.K. Ministry of Defence, 1998. Available: *www.ipfmlibrary.org/mod98.pdf*.

8 *Plutonium and Aldermaston – An Historical Account*, U.K. Ministry of Defence, 2000. Available: *http://fissilematerials.org/library/mod00.pdf*.
Historical Accounting for UK Defence Highly Enriched Uranium, U.K. Ministry of Defence, 2006. Available: *www.ipfmlibrary.org/mod06.pdf*.

9 A. Glaser and M. Göttsche, "Fissile Material Stockpile Declarations and Cooperative Nuclear Archaeology," in *Verifiable Declarations of Fissile Material Stocks: Challenges and Solutions*, United Nations Institute for Disarmament Research, 2017.

10 *The United States Plutonium Balance, 1944-2009*, 2012, op. cit.

11 M. Göttsche, "Nuclear Archaeology to Assess Fissile Material Inventories for Nuclear Safety and Security, Transparency and Disarmament," *Nonproliferation Review,* 2021.

12 See, for example, A. von Baeckmann, G. Dillon and D. Perricos, "Nuclear verification in South Africa," *IAEA Bulletin*, no. 1, 1995, pp. 42-48.

13 R.E. Kelley, *A Technical Retrospective of the Former South African Nuclear Weapon Programme*, SIPRI, 2020.

14 O. Heinonen, "Verification of the Correctness and Completeness of Initial Declarations," *Symposium on International Safeguards Verification and Nuclear Material Security*, Vienna, 2001.

15 *Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols*, IAEA Services Series 21, International Atomic Energy Agency, Vienna, May 2016.

16 The online enrichment monitor measures the characteristics of gaseous uranium – UF_6 – flowing through the processing pipes out of the cascades of centrifuges of the enrichment plant. In each unit of the equipment, the main connection node, a gamma ray detector based on a sodium iodide crystal, measures the amount of U-235 in the pipe, while pressure and temperature sensors enable the machine to determine the total quantity of gaseous uranium. From the two, the device can calculate the enrichment level, which can be checked by inspectors on the site.

17 *Safeguards Implementation Report 2019*, GOV/2020/8/Annex, International Atomic Energy Agency, Vienna, 2019.

18 In January 2020, the United Kingdom withdrew from the European Union and, consequently, also EURATOM. EURATOM stopped inspecting United Kingdom facilities in January 2021, when the U.K.'s Office of Nuclear Regulation assumed safeguards and nuclear material accountancy duties. The Capenhurst uranium enrichment facility, which was subject to EURATOM safeguards, could be inspected by the IAEA if it appears on the United Kingdom's voluntary offer list.

19 H. Zhang, "China is speeding up its plutonium recycling programs," *Bulletin of Atomic Scientists*, 76 (4), 2020, pp. 210-216.

20 According to a Tripartite Agreement between China, Russia, and the IAEA, Russian-built plants in China are available for safeguarding, but only the Hanzhong gas centrifuge plant in Shaanxi has been subject to IAEA safeguards (since China is a nuclear weapons state, safeguarding additional facilities is a low priority for the IAEA). See M.D. Laughter *Profile of World Uranium Enrichment Programs – 2009*, ORNL/TM-2009-110, Oak Ridge National Laboratory, April 2009. Available at: *https://fas.org/nuke/guide/enrich.pdf*.

21 Special nuclear material can be used in a wide array of military purposes that are not explosive – for power or heat sources, for example. It is unlikely that the IAEA has developed safeguards for those other kinds of purposes, although there has been some thinking about how to safeguard naval fuel, albeit without conclusion, since the need for such safeguards has not yet arisen.

22 500 metric tons of Russian HEU was blended down into LEU for U.S. civil nuclear fuel under the Megatons to Megawatts program from 1993 to 2013. The United States declared 174.3 metric tons of HEU surplus to defense needs in December 1994. Some has been downblended into LEU for civilian power reactor fuel. In 1995, President Clinton announced that 200 tons of HEU and plutonium would be removed from the stockpile. In the United States, just 8 tons of its total 87.7 tons of unirradiated plutonium is civilian. In its remaining military stockpiles of 79.7 tons, more than half (49.3 tons) was declared as excess material in the early 1990s. The United Kingdom declared 4.1 metric tons of non-weapon grade plutonium and 0.3 metric tons of weapon-grade plutonium as excess to military requirements.

23 *Strategic Defence Review: Modern Forces for the Modern World*, 1998, op. cit..

24 M.W. Goodman and J.S. Adams, "Status of the Implementation of IAEA Safeguards in the United States," *60th INMM Annual Meeting*, 2019.

25 See, for example, *International Safeguards in the Design of Reprocessing Plants*, IAEA Nuclear Energy Series No. NF-T-3.2, International Atomic Energy Agency, Vienna, 2019. Available: *https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1866_web.pdf*.

26 The IAEA Safeguards glossary defines Significant Quantity as " the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses. Significant quantities are used in establishing the quantity component of the IAEA inspection goal (see No. 3.23). For plutonium containing less than 80% Pu-238, it is 8 kg; for U-233 it is 8 kg; for U-235 enriched 20% or more, it is 25 kg; for U-235 enriched < 20% it is 75 kg, 10 tons for natural uranium and 20 tons of depleted uranium; and 20 tons of thorium. *IAEA Safeguards Glossary*, International Atomic Energy Agency, Vienna, 2001. Some experts have made the case that IAEA safeguards are inadequate even as applied to non-nuclear weapon states. See, for example, T.B. Cochran, "Adequacy of IAEA Safeguards for Achieving Timely Detection," NPEC/King's College conference *After Iran: Safeguarding Peaceful Nuclear Energy*, London, United Kingdom, October 2-3, 2005. Available: *http://www.npolicy.org/article_file/Adequacy_of_IAEAs_Safeguards_for_Achieving_Timely_Detection-PAPER.pdf*.

27 *Multilateral Approaches to the Nuclear Fuel Cycle,* Expert Group Report to the Director General of the IAEA, International Atomic Energy Agency, Vienna, 2015. Available: *https://www.iaea.org/publications/7281/multilateral-approaches-to-the-nuclear-fuel-cycle.*

28 In theory, IAEA safeguards increase in their intrusiveness for facilities that produce HEU rather than LEU. However, this has not been tested, since HEU production facilities have not heretofore been safeguarded by the IAEA.

29 R. Higgy and D. Fischer, "Detection of Reprocessing Activities Using Environmental Sampling," *Symposium on International Safeguards*, Vienna, 2014.

30 *Global Fissile Material Report 2008*, International Panel on Fissile Materials, 2008, p. 46.

31 The Hexapartite Safeguards Project defined safeguards approaches for centrifuge enrichment plants. Australia, Germany, Japan, the Netherlands, the United Kingdom, the United States, the European Atomic Energy Community (EURATOM), and IAEA participated. Under HSP, enrichment facilities with a stated enrichment of 5 percent or less require inspections inside and outside the cascade. Inside the cascade, the Limited Frequency Unannounced Access inspections are designed to detect enrichment levels higher than stated amounts. See *INFCIRC/640*, International Atomic Energy Agency, 2005, p. 53.

32 *Verifying Baseline Declarations of Nuclear Warheads and Materials*, Nuclear Threat Initiative, 2014. Available: *https://media.nti.org/pdfs/WG1_Verifying_Baseline_Declarations_FINAL.pdf*.

33 See, for example, G. Baldwin, *A Systematic Approach for Implementing Managed Access at Sensitive Nuclear Facilities*, unpublished discussion paper prepared for Department of Energy and Sandia National Laboratories in 2000. Available: *https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/016/32016765.pdf*.

34 M. Göttsche, "The Grand Picture of Verifying Nuclear Disarmament: What Needs to be Done," *Bulletin of the Atomic Scientists,* 2018.

35 P. Podvig and J. Rodgers, *Deferred verification: verifiable declarations of fissile-material stocks for disarmament purposes,* UNIDIR, 2017.

36 S. Philippe, "Safeguarding the Military Naval Nuclear Fuel Cycle," *JNMM*, XLII (3), 2014, pp.40-52.

37 See collection of essays on *Reducing Risks from Naval Nuclear Fuel*, Institute for International Science & Technology Policy, IISTP-WP-20818-10, Occasional Papers Series, George Washington University, October 2018. Available at: *https://cpb-us-e1.wpmucdn.com/blogs.gwu.edu/dist/c/1963/files/2018/10/Occasional-Papers_Reducing-Risks-from-Naval-Nuclear-Fuel-2anfj76.pdf*.

38 See S. Fetter and F. von Hippel, "A Step by Step Approach to a Global Fissile Materials Cutoff," *Arms Control Today,* 25 (8), Oct 1995, pp. 3-8. Available: *https://fas.org/programs/ssp/nukes/armscontrol/95actfmct.pdf.*

39 L.G. Fishbone and J. Sanborn, *Routine Inspection Effort Required for Verification of Nuclear Material Production Cutoff Convention*, BNL-61304-Informal, SSN-94-21, Brookhaven National Laboratory, Dec 1994. Available: *https://www.osti.gov/servlets/purl/31704/*. Their calculations suggested that a full-scope safeguards approach in states with nuclear weapons would quadruple the person days of inspection conducted by the IAEA at that time; the most minimal verification option for FMT (just enrichment and reprocessing) would double it. Large scale reprocessing plants back then required 900 person days of inspection. The 1994 estimate did not include North Korea.

40 For example, see, *Affordable Cleanup? Opportunities for Cost Reduction in the Decontamination and Decommissioning of the Nation's Uranium Enrichment Facilities*, Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities, Board on Energy and Environmental Systems, Commission on Engineering and Technical Systems, National Research Council, Washington, DC, 1996.

41 For a description of the step-by-step process France followed to dismantle and decommission its high uranium enrichment plant for defense purposes at the Pierrelatte site, see: C. Behar, et al. "D&D of the French High Enrichment Gaseous Diffusion Plant," *WM 2003 Conference*, Tucson, Arizona, February 23-37, 2003. Available: *https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1066.4602&rep=rep1&type=pdf*.

42 M. Göttsche, 2021, op. cit..

43 This is a bare minimum; the case for more comprehensive safeguards (reactors, other elements of the fuel cycle) can also be made.

44 See, for example, the 2008 Fissile Material Control Initiative, proposed by former Assistant Secretary of State Robert Einhorn: R. Einhorn, "Controlling Fissile Materials Worldwide: A Fissile Material Cutoff Treaty and Beyond," in G. Shultz, S. Andreasen, S. Drell and J. Goodby, eds., *Reykjavik Revisited,* Hoover Institution Press, Stanford, CA, 2008, pp. 181-182.

45 See Endnote 2.

46 D. Holloway, "Steps toward a World Free of Nuclear Weapons," in C. Kelleher and J. Reppy, eds., *Getting to Zero. The Path to Nuclear Disarmament*, Stanford University Press, 2011, pp. 347-358.

47 T. Patton and A. Glaser, "Deferred verification: the role of new verification technologies," *Nonproliferation Review,* 26 (3-4), 2019, pp. 219-230.

48 S. Fetter and I. Oelrich, "Verifying a Prohibition of Nuclear Weapons," in B. Blechman, ed., *Elements of a Nuclear Disarmament Treaty*, 2010.

49 For fusion reactors that rely on deuterium-tritium reactions, there will be a potential need for fission reactors to produce tritium, since the fusion reactors may not produce enough. For fusion reactors that rely on just deuterium, there is the potential for clandestine production of Pu-239 by inserting U-238 into reactors. This would still require IAEA safeguards or some other monitoring. D. Jassby, "Nuclear Fusion Reactors: Not what they're cracked up to be," *Bulletin of Atomic Scientists*, April 2017. Available: *https://thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/*.

4. Nuclear Monitoring and Verification Without Onsite Access

ALEXANDER GLASER AND IRMGARD NIEMEYER

ABSTRACT. *This chapter examines the possible contributions of remote and standoff monitoring for nuclear disarmament verification. In this context, satellite imagery could play a particularly important role. As spatial resolution of satellite imagery has increased to a level where further improvements are no longer critical, the technology is currently experiencing a second revolution thanks to high satellite-revisit rates, often multiple times per day, and thanks to broader access to satellite imagery by governments and the public. Other, complementary technologies that could reduce the importance of onsite inspections are wide-area environmental monitoring, which involves the regional collection of atmospheric or other samples, and perimeter monitoring, which seeks to confirm the declared operational status of a facility by treating it as a "black box" and drawing conclusions only by looking at items and materials as they enter or leave the facility. The chapter reviews the state-of-the-art of these technologies. It also assesses their potential for confirming the non-operational status or throughput of fissile-material production facilities and for monitoring nuclear weapons deployment, production, storage, dismantlement sites. While not the main focus of this chapter, we also examine the evolving role of remote monitoring techniques for the detection of undeclared facilities and activities. Relevant tasks include the ability to detect undeclared uranium mines, undeclared fissile material production, and undeclared weapons production or storage sites.*

Introduction

Onsite inspections play an important role in verifying compliance with nuclear nonproliferation and arms control agreements. Recent advances in remote and standoff monitoring may complement such inspections, which could make verification approaches more robust, less intrusive, and possibly also less expensive. Among the possible monitoring technologies and approaches, satellite imagery, wide-area environmental monitoring, standoff detection, and perimeter surveillance are often considered most promising for verifying nuclear disarmament without on-site access.

Satellite imagery has historically played a unique role in arms control verification. Today, satellite imagery also represents a key source of information for the implementation and verification of Nuclear Non-proliferation Treaty (NPT). Together with auxiliary data, it can be used as a reference source to aid in field and inspection planning, to detect changes and monitor activities at nuclear facilities, to verify the completeness and correctness of information supplied by a member state as well as to investigate alleged illegal activities related to nuclear nonproliferation, arms control or disarmament.[1] As spatial resolution of satellite imagery has increased to a level where further improvements are no longer critical, the technology is currently experiencing a second revolution thanks to high satellite-revisit rates, often multiple times per day, and thanks to broader access to satellite imagery by governments and the public.

Another technology that could complement onsite inspections is wide-area environmental monitoring, which involves the collection of atmospheric or other samples. This technique has the potential to detect undeclared activities or facilities on a regional and perhaps even global scale. Wide-area environmental monitoring could also be used in the vicinity of declared plants to confirm declared activities and reduce requirements for onsite access.

Yet another technology to consider is perimeter monitoring, which seeks to confirm the declared operational status of a facility by treating it as a “black box” and drawing conclusions only by looking at items and materials as they enter or leave the facility. Virtually any nuclear site has a security perimeter, typically set up and controlled by the host state or the operator of the plant. The main purpose of this perimeter is to deter, detect, and prevent unauthorized access to the plant and to prevent theft of nuclear materials or components, which is a concern for both insider and outsider threats.[2] It is only natural to consider building on this existing infrastructure to support independent monitoring of a site for verification purposes. This concept is particularly valuable for sites where inspector access is considered difficult, for example, due to security concerns raised by the host.

The chapter reviews the current state-of-the-art of these technologies and examines the ways in which they could support future disarmament verification regimes. In particular, the discussion highlights their potential for confirming the non-operational status or throughput of fissile-material production facilities and for monitoring nuclear weapons deployment, production, storage, dismantlement sites. While not the main focus of this chapter, we also examine the evolving role of remote monitoring techniques for the detection of undeclared facilities and activities. Relevant tasks include the ability to detect undeclared uranium mines, undeclared fissile material production, and undeclared weapons production or storage sites.

Technologies and Approaches

There are a number of technologies that could help reduce the requirements for onsite inspections in an arms control context. Before we consider specific verification objectives and approaches in the next section, here we summarize briefly the technical basics for those technologies that are most relevant or promising for this purpose.

Satellite imagery

While the era of military satellite reconnaissance began in 1960 with the U.S. Corona program, earth observation (EO) for civilian purposes started 1972 with the launch of Landsat-1 by the U.S. National Aeronautics and Space Administration (NASA). Landsat-1 recorded image data in three spectral bands (green, red, and near infrared) with a spatial resolution of 80 m. With the launch of IKONOS-2 in 1999, which provided a spatial resolution of one meter for the first time, the use of very high-resolution satellite imagery for monitoring nuclear sites and activities (for example, by the IAEA) gained greatly in importance.[3] Since then, EO solutions have continued to expand and diversify, in terms of spatial, spectral, and temporal resolution of image data, and in national ownership. More and more countries have planned to launch EO satellites in order to respond to national policy or security interests, to assist in developing a national space infrastructure, and to expand current commercial data offerings.

Sensor	Company (Country)	Launch date	No. of satellites	Spatial resolution (in m)	Swadth (in km)
Optical sensors					
WorldView Legion	*Maxar Techn. (USA)*	*2021*	*5 ?*	*0.29 (PAN)* *1.16 (VNIR)*	*tba*
WorldView 3	Maxar Techn. (USA)	08/2014	1	0.31 (PAN) 1.24 (VNIR) 3.7 (SWIR)	13.1
EROS-C	ImageSat Int. (Israel)	2020	1	0.38 (PAN) 0.76 (VNIR)	11.5
Geo-Eye 1	Maxar Techn. (USA)	09/2008	1	0.41 (PAN) 1.65 (VNIR)	15.3
WorldView 2	Maxar Techn. (USA)	10/2009	1	0.46 (PAN) 1.85 (VNIR)	1.4
WorldView 1	Maxar Techn. (USA)	09/2017	1	0.50 (PAN)	17.1
SuperView-1/ GaoJing-1	Beijing Space View Techn. (China)	12/2016 01/2018	4	0.50 (PAN) 2.0 (VNIR)	12.0
Synthetic aperture radar (SAR) sensors					
TerraSAR-X Tandem-X	Airbus Defense and Space (Germany)	06/2007 10/2010	2	Down to 0.25*	4 x 3.7 or 2.5 x 7.5*
ICEYE	ICEYE (Finland)	01/2018- 07/2019	5 (up to 18)	Down to 0.25*	5*
Capella-2/ Sequioa	Capella Space (USA)	08/2020	1 (up to 36)	Down to 0.3*	5 x 20 or 10 x 10*

Very high spatial resolution imaging sensors, ordered by spatial resolution (<0.5m). PAN: panchromatic; VNIR: visible and near infrared spectrum; SWIR: shortwave infrared spectrum. Sources: www.satimagingcorp.com/satellite-sensors; Operators' websites; Earth Observation Portal at *directory.eoportal.org*; Observing Systems Capability Analysis and Review Tool (OSCAR) at *www.wmo-sat.info/oscar*. *) depending on acquisition mode (here: highest spatial resolution possible)

The advent of small satellites has led to another revolution in earth observation. Small satellites typically have a mass of less than 500 kg and are smaller than a kitchen stove, but they can still deliver sub-meter resolution imagery and high-definition videos. Due to much lower costs associated with development and launch, large constellations of small satellites have become possible, which enables for more frequent revisits, monitoring, and change detection of areas of interest. While existing satellite constellations can already take daily snapshots of the entire planet, a time resolution on the order of hours could soon be possible. The table above lists the very high-resolution earth observation sensors in space today, providing imagery at a resolution of better than one meter.

Optical sensors operate in the optical region of the electromagnetic spectrum traditionally defined as radiation with wavelengths between 0.4 and 15 μm. The specific wavelengths within the electromagnetic spectrum that are observable to satellite borne sensors are well understood and therefore the majority of earth observation satellites collect wavelengths in regions that have the highest potential for information to be collected by the sensor. These areas include visible wavelengths, near-infrared, thermal and radio wavelengths. The visible and near infrared (VNIR) wavelengths are very common for image analysis since they are the easiest for humans to visually interpret as they closely match with the wavelengths the human eye can detect. Commercially available sensors with high spatial resolution record information in these bands. Some of these sensors, such as the Worldview-3 sensor, also collect information in the shortwave infrared whereas others, like Kompsat-3A, collect in the mid infrared.

While these multispectral sensors acquire data in a number of bands covering only parts of the electromagnetic spectrum, hyperspectral sensors record the reflected radiation in several hundreds of very narrow contiguous or overlapping wavelength bands, providing a continuous spectrum from the visible to shortwave infrared. As specific surfaces leave unique fingerprints in the electromagnetic spectrum (also known as spectral signatures), hyperspectral data allows for identification of surface materials. New spaceborne hyperspectral sensors have been launched recently (DESIS, PRISMA, and Jilin-1) and others will be launched in coming years. However, the low temporal resolution (revisit time) and the medium spatial resolution of 20–30 m for some of these sensors may be a limiting factor for the application of spaceborne hyperspectral data for arms control and disarmament verification.

Synthetic Aperture Radar (SAR) is a valuable active sensor type since it penetrates most cloud cover and offers a different set of information for interpretation compared to optical sensors. SAR data requires a different set of processing techniques and demands a different approach for processing and analysis compared to the other earth-observation sensors mentioned above. The frequency bands generally used for these activities are the X, C, and L bands. Some of the commonly used SAR sensors include TerraSAR-X, TanDEM-X, COSMOS-Skymed, Capella, Radarsat, and Sentinel-1 SAR.

As satellite imagery providers deploy new constellations of satellites, with the aim of images covering all landmasses in the world several times a day, the quality and quantity of this data is increasing rapidly as are the methods to process and analyze the datasets. The resulting repositories of satellite imagery will offer analysts distinct insights into nuclear facilities and nuclear activities from space worldwide. The deluge of data, together with the variety of related metadata, however, requires the further automation of pre-processing, in order to produce geometrically and spectrally corrected input imagery, including data file conversion to a model standard, orthorectification and co-registrations, radiometric normalization and screening for artefacts caused by clouds, cloud-shadow, snow, and other confounding factors.[4] Advancements of methods are also necessary for extracting the relevant information from satellite imagery, such as infrastructure changes, as visual interpretations of single satellite image scenes can no longer be expected to address the analysis requirements for such large satellite imagery repositories. New robust data science methods can offer analysts automated alerts that flag for instance changes occurring within a nuclear facility's infrastructure.[5] If changes were detected, automated prompts and traditional manual evaluations by analysts of change would then be initiated. A number of studies have demonstrated the potential of data science methods for nuclear verification, such as statistical time series analysis, deep learning methods, and convolutional neural networks.[6]

Wide-area environmental monitoring

The IAEA has been using *location-specific* environmental swipe sampling techniques for safeguards purposes since the 1990s. This sampling technique is used on a routine basis during inspections of a variety of nuclear-fuel cycle facilities today, and it has proven very effective and inexpensive and is considered a mature technology. While swipe sampling could also play a relevant role in nuclear disarmament verification, for example, by providing confidence in the absence of certain materials at specific facilities, it requires access to the inspected facility and is therefore not part of the discussion here.[7] Beyond location-specific environmental sampling, the 1997 Additional Protocol also considered the use of wide-area environmental sampling (WAES), which it defined as follows:

"Wide-area environmental sampling means the collection of environmental samples (e.g., air, water, vegetation, soil, smears) at a set of locations specified by the Agency for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities over a wide area" (INFCIRC/540, Article 18).

Wide-area environmental sampling is not currently used for IAEA safeguards purposes, and it would have to be first approved by the IAEA Board of Governors before it could be.[8] Already in February 1995, however, the IAEA Secretariat concluded that environmental monitoring is "an extremely powerful tool for gaining assurance of the absence of undeclared activities at and near such nuclear sites."[9] In order to further clarify the potential of WAES, an extensive study set out to determine the feasibility, practicability, and costs of environmental monitoring techniques to detect undeclared nuclear activities on a country-wide or large-area basis, particularly in areas that do not contain declared nuclear or nuclear-related sites.[10] STR-321 found that atmospheric sampling appeared to be the technique with the greatest detection probability per sample of those sampling methods that were considered. However, the costs of operating a sensor network could be very high and would strongly depend on the type of facility or activity, the target region covered, and the acceptable probability of detection and false-alarm rate. Overall, undeclared plutonium separation (reprocessing of spent fuel) would be more easily detectable than most other relevant activities. Gas-centrifuge uranium enrichment plants would be most difficult to detect, which has been confirmed by some other studies later on.[11] STR-321 also highlighted the uncertainties in the analysis and pointed out that additional work would be useful in validating some of the key assumptions used as input to the study on which the results heavily depended. Research on WAES continues, and several promising new techniques and approaches have emerged since STR-321 was first published.

The original IAEA definition of WAES is relatively narrow as it only considers the collection of *physical* samples. The IAEA also assumed that some form of local or regional access would be required and that, for the same reason, the host party would be collaborating with the effort and even accompany the inspectors at all times. Below, we consider a broader view of WAES and, specifically, use the word "monitoring" instead of "sampling" (WAEM vs WAES). In particular, a collection of physical samples may not always be necessary for WAEM; for example, laser-based techniques (such as LIDAR) could probe the air above a suspected location to detect trace amounts of gases or particulates, and anti-neutrino detectors could detect undeclared reactors from a distance. Similarly, the seismic, acoustic and radionuclide stations of the International Monitoring System (IMS) operated by the CTBTO could be considered part of a WAEM network. Data from different sensor platforms could be combined to enable a more robust monitoring network that relies on more than one signature. Finally, the use of airborne sensors may not always require the active collaboration of the inspected party if the use of such a platform has been generally agreed upon and formalized as part of a [regional, bilateral or multilateral] arms control agreement. There have been several important technical developments since the first extensive studies of WAEM in the 1990s that have the potential to make the approach more viable today; they include:

Availability of mobile sensor/detector platforms. The last decade has seen disruptive advances in drone or unmanned-aerial-vehicle (UAV) technology used for a variety of civilian and military purposes.[12] Deploying sensors for WAEM on drones or swarms of drones could have fundamental advantages compared to fixed sensor networks. First, they could be deployed regionally, for example, as part of a regional arms control agreement. Second, given the dynamic nature of the network, mobile platforms could provide higher levels of assurance as their "behavior" is more difficult to predict and non-compliance therefore more difficult to conceal.

Advances in data science and machine learning. Large datasets of noisy sensor data could be processed by advanced machine-learning techniques that have only become available over the past few years.[13] This automated process may flag suspect patterns in the data so that a safeguards or verification specialist can further examine the region or location. There are numerous efforts underway that seek to quantify the potential of data analytics using data-fusion from multiple sensor platforms. Such efforts are often based on the premise that single-modality analysis cannot "deliver a global-scale, real-time capability to detect, locate, and characterize low-profile proliferation."[14]

State-of-the-art modeling capabilities. Atmospheric signatures are generally considered most promising for several types of nuclear fuel-cycle facilities. Here, the atmospheric-transport modeling (ATM) capabilities have increased dramatically over the past two decades. This is often driven by research and development in the area of climate science and supported by much improved weather data availability. ATM can be used for backward and forward modeling. In the case of backward modeling, ATM can be used to identify possible source locations and time of release once an unusual activity is detected; in the case of forward modeling, given a suspect location or event, ATM can be used to determine the best sampling locations for an upcoming campaign in real time. Still, in many circumstances, the usefulness of such modeling efforts would rely on available baseline data, which would include in particular emissions from declared facilities. In order to maximize the usefulness of ATM and of WAEM in general, declarations of emissions from nuclear facilities worldwide would be very beneficial. For example, operators of commercial reprocessing plants could provide daily or hourly data on krypton-85 emissions. So far, operators have been reluctant to do so.

Standoff-detection is considered here as a special, targeted variation of wide-area environmental monitoring. In this case, the facility is known and declared, but access to the site itself is difficult or impractical for security or safety reasons. The same signatures and sensor types that can be considered for WAEM are also relevant for standoff-detection, but the host would actively support or accept the deployment of sensors near the site. The main use case for standoff detection could be at some known military, sensitive facilities to avoid or minimize access for inspectors. Many of the challenges associated with large-scale (regional) WAEM, which seeks to provide confidence in the absence of undeclared facilities, are much less pronounced in the case of standoff detection given the proximity of the sensors to the site that is being monitored. For example, it is relatively easy to confirm the operational status of nearby reactors using antineutrino detectors; it is vastly more difficult to detect them at larger distances for "regional reactor discovery" as further discussed below.

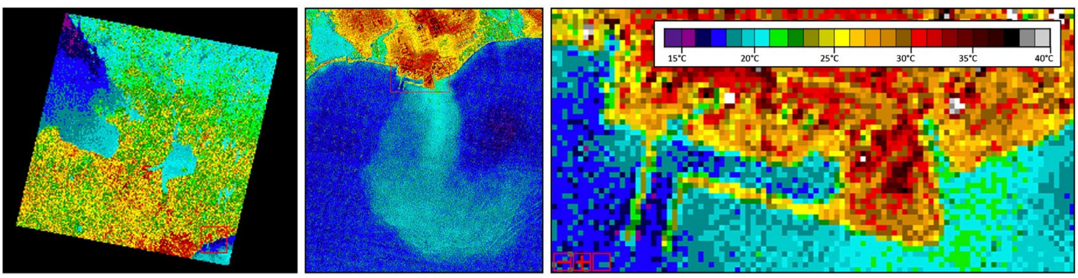
Perimeter portal control continuous monitoring

Perimeter monitoring could play a future role to support nuclear disarmament verification by reducing the need for onsite inspections at sensitive sites associated with a nuclear weapons program. Indeed, verification of the Intermediate Nuclear Forces (INF) Treaty relied extensively on perimeter monitoring at two ballistic missile production sites in the United States and the Soviet Union. The technology has some important drawbacks, however, which has so far limited its general adoption for verification purposes. In particular, the IAEA has been reluctant to adopt perimeter control as part of its safeguards system; there are various reasons for that. First, the IAEA deals mostly with nuclear materials, often in bulk form, whereas INF required monitoring of large and bulky missile stages and rocket motors. Perimeter control with portal monitors becomes more challenging as the items of inspection become smaller and more difficult to detect. Second, by monitoring the perimeter only, one cannot preclude that prohibited activities are conducted within the facility, which may enable some "fait-accompli" breakout scenarios and make timely detection of non-compliance difficult or impossible. Third, perimeter control tends to be costly, in particular, because it typically requires resident inspectors. For example, INF inspections were extremely expensive compared to IAEA safeguards costing about 50% of the IAEA budget at the time, which covered at the time more than 900 facilities in almost 60 countries.[15] Finally, and perhaps most importantly, the IAEA generally avoids physical security-like measures as part of its inspection activities; in particular, it's not part of the IAEA culture to conduct personal or vehicle searches, beyond its authority. Scheinman and Kratzer (1992) acknowledged that "the rejection of perimeter monitoring under NPT-IAEA is at least partly attributable to institutional and attitudinal factors that have tended to overemphasize the need for complete materials balance accountancy and place unnecessary restrictions on the use of surveillance and containment measures." Overall, with few exceptions, there is relatively little experience with perimeter portal continuous monitoring for verification purposes, and the most important effort ended when the inspection regime of the INF treaty ended in 2001.

Given its low salience as a verification technology, technologies relevant for perimeter control have developed slower than in other areas. Today, there exist advanced and more sensitive instruments, which enable measurements that were previously impractical. Machine learning techniques have further enabled characterization of radiation signatures even when the signal-to-noise ratio is extremely low. The "Miniature Integrated Nuclear Detection System" (MINDS) is able to identify radioactive sources within seconds, for example, in automobiles that stop or slow down at a toll booth.[16] The system uses a supervised machine-learning algorithm and can be trained with large data sets to make it robust against false-positives. The system also senses intentionally concealed or mask radiation signatures, for example, when attempts are made to pass shielded containers through a portal monitor. Systems like these have yet to be tested on a broader scale for verification applications.

Monitoring Regimes and Verification Objectives and Approaches

We consider a number of verification objectives for possible future arms control treaties. Such agreements could include limits on the number of nuclear weapons, including those in storage, or a ban on certain weapon types. We also consider objectives that could be relevant for agreements that constrain the production or use of fissile material for military purposes such as a fissile material (cutoff) treaty or the monitored international storage, disposition, or elimination of excess materials. In many cases, sensitive military nuclear sites would have to be monitored, and minimizing the need for onsite inspections may often be considered advantageous.



Surface temperatures at a nuclear power plant, analyzed based on LANDSAT-7 image acquired over the site in August 2002. Using the temperature information from the thermal band (60 m spatial resolution), the surface temperatures can be displayed on a given scale. For better illustration of the temperature distribution on the surface, they were fused with the 15-m panchromatic band.

Confirming non-operational status of fissile-material production facilities

The operation of nuclear facilities is associated with some specific activities or features on the earth surface, such as vehicles in parking spaces, delivery traffic and equipment. While these types of surface objects and their movements can easily be monitored using very high-resolution satellite imagery, the existence of thermal emissions could give the essential indication that a facility is in operation. The absence of these activities and features on the surface can be used to confirm the non-operational status of nuclear facilities, and, depending on the type of facility, thermal infrared imagery can play an important role in this context. However, spaceborne thermal infrared sensors with a commercial payload are limited to the Landsat-8 and ASTER sensors with a spatial resolution of 120 m and 90 m, respectively. Since no developments as to spatial resolution are expected for commercial sensors soon, they will remain the only source of thermal infrared information from space for the medium-term future.

Despite the poor resolution, thermal infrared remote sensing data can provide verification-relevant information in case of significant thermal signatures of the facility. After converting the thermal infrared data to emissivity and temperatures, image fusion with bands of higher spatial resolution facilitates the interpretation of the temperatures. Using anomaly detection tool are useful for extracting “hot spots” in a specific region or the whole scene (see figure).

Confirming production-as-declared status of fissile-material production facilities

In general, it is easier to verify the absence of something than it is to verify an upper or declared limit. This is also true for nuclear fuel-cycle facilities, where it is much easier to verify the shutdown status than the throughput of a plant. Onsite access to sites and facilities is always desirable for confirming the “operation-as-declared” status of plants but remote or standoff monitoring may be preferable in some circumstances due to security or other concerns. Here, we are particularly interested in nuclear reactors, reprocessing plants, and uranium enrichment plants.

Nuclear reactors. From a verification perspective, the main concerns associated with the operation of nuclear reactors are activities that could be related to undeclared plutonium production; these include high-than-declared power levels of the reactor, undeclared irradiation of target materials in the core, and diversion of irradiated or spent fuel from the reactor core or the spent fuel pool. The relative importance of these distinct concerns varies between research reactors (10–100 MW thermal) and power reactors (1000–3000 MW thermal), but traditional safeguards have proven very effective in addressing them. In the case of nuclear weapon states, possible exceptions may include some high-powered research reactors that are partly or primarily used for military applications, including for example tritium production or irradiation testing of naval fuel. In these circumstances, there could be a complementary role for perimeter or standoff monitoring of these sites. In particular, there has been some interest in detecting antineutrinos, which are emitted in the fission process and can confirm the operational status and power levels of nuclear reactors. To a more limited extent, this method can also be to track fuel changes over time.[17] Given the complexity and costs of the technology, the use of antineutrino detectors for reactor monitoring is often considered impractical, especially if the same verification objectives can be achieved with other, more traditional means.

Uranium enrichment plants. The IAEA has significant experience with safeguarding centrifuge enrichment plants.[18] In recent years, safeguards approaches have been strengthened further, and they now also include instruments that enable real-time monitoring of the enrichment level of the product using the "Online Enrichment Monitor" (OLEM), an instrument currently used in Iran.[19] Similarly, it may be possible to also monitor in real-time the throughput of a gas-centrifuge enrichment plant, which together with enrichment monitoring provides a complete picture of ongoing operations and allows timely detection of a "breakout."[20] The very same safeguards technologies and approaches could be used in nuclear weapon states; in fact, centrifuge enrichment plants in France, the United Kingdom, and the United States are already under IAEA safeguards. There is far less experience with safeguards on plants using Russian and Chinese centrifuge technology, and there is no experience in India, Pakistan, North Korea, and possibly Israel.

There is one potential use case for perimeter monitoring at very large enrichment plants that are unsafeguarded today and where implementation of traditional safeguards techniques could be considered too complicated or insufficient, especially when retrofitted into an already existing plant. In fact, in the 1970s, perimeter monitoring was considered as a safeguards approach for plants under construction or planned at the time.[21] Fundamentally, the concept is based on tracking and measuring the material entering and leaving the plant. The number of UF_6 cylinders involved is relatively small even for a plant with a capacity in the million SWU/yr range (see figure). Based on these measurements, the separative work of the plant could be independently estimated, though not necessarily in a timely manner. In the context of a fissile material cutoff treaty or a declared moratorium on fissile material production, this approach could also be used to infer the non-production of HEU. While it could be difficult to detect extraction of the highly enriched material from the site (due to its small volume, as illustrated in the figure below), there would be a significant and easily detectable shortfall in the expected low-enriched product leaving the plant.

Reprocessing plants. Safeguarding reprocessing plants is very difficult and expensive even in non-nuclear weapon states where the IAEA may be involved in the planning and construction stages of the project; in fact, once operational, Japan's Rokkasho plant would absorb about 50% of the current IAEA inspection effort. Concepts for safeguards at reprocessing plants in weapon states under a Fissile Material Cutoff Treaty would be very similar to those developed for Rokkasho.[22] Retrofitting safeguards into existing plants would be extremely difficult and, in some cases, impossible. As an interim measure, perimeter monitoring could play a limited role, and monitoring of krypton emissions directly at the stacks could be used to estimate declared plutonium production at the plant. Altogether, from a verification perspective, it would be much preferable to shut down these few existing plants that are unsafeguarded today.

Uranium entering and leaving a large enrichment plant over a two-week period. Shown on the left are the feed cylinders needed to supply natural uranium for a one-million SWU/yr plant and the product cylinders that can be produced with this material. Shown on the right is a misuse scenario, where one significant quantity of HEU is produced. While it may be difficult to detect the removal of small HEU cylinders from the plant, a significant amount of LEU product is unaccounted for. A verification approach based on perimeter portal continuous monitoring may be able to confirm as-declared operation of such a plant without onsite access.

Monitoring nuclear weapons deployment, production, storage, dismantlement sites

Nuclear weapons deployment, production, storage, and dismantlement sites can be considered the most difficult sites to capture with onsite inspections. At all these sites, there are extraordinary safety and security concerns, which also apply to workers and personnel but are exacerbated for international inspectors. Among these facilities, there is some experience with access for inspectors to deployment sites, especially under INF and START,[23] but even here remote monitoring has played a critical role.

The 1972 SALT agreements first introduced the concept of using satellites (falling under “national technical means”) for verification purposes, and the parties undertook “not to interfere with the national technical means of verification of the other party” and “not to use deliberate concealment measures” (SALT, Article V). START expanded on this concept by introducing cooperative measures; in particular, at the request of the other party, road-mobile launchers of ICBMs could be openly displayed by opening the roofs of their garages with the launchers located “next to or moved halfway out of such fixed structures”

(START, Article XII). Future arms control agreements could similarly rely on satellite imagery to confirm numerical limits on launchers; it is unlikely, however, that satellites could play a primary role in confirming warhead limits at deployment or other types of facilities in this category. Warheads are small and can be moved more quickly in inconspicuous vehicles. In any event, quasi continuous monitoring of a site using satellites has to be considered difficult and perhaps impractical even with large satellite constellations. Very few countries have the capabilities to re-task satellites on short notice, and quasi-continuous monitoring is further constrained by cloud coverage and nocturnal periods, during which optical satellites cannot be used for most monitoring missions.

In anticipation of short-notice (challenge) inspections, satellite reconnaissance may be considered appropriate to monitor the standdown status of a site during a limited amount of time, for example, to confirm that no large trucks enter or leave the site during a well-defined, limited time window before inspectors arrive at the site.

Given the presence of highly sensitive items and operations at weapons assembly, maintenance, and dismantlement sites, onsite inspections at these sites would have to rely on managed-access concepts.[24] While possible and successfully used on a small scale in the past, managed-access inspections are complex and would be particularly challenging at sites where warheads are produced or maintained. It is possible that, in some cases, perimeter control without onsite access would be a preferable and more viable approach for such sites; only when the active use of a site ceases, a close-out inspection would be used to confirm the absence of all treaty accountable items or activities.

The 1987 Intermediate Nuclear Forces (INF) Treaty between the United States and the Soviet Union pioneered the concept of perimeter control for arms control purposes.[25] As part of the treaty, both parties had the right to monitor the portals and to patrol the perimeter of one missile production site in each country for up to thirteen years, i.e., from 1988 through 2001. Up to 30 resident inspectors were allowed at the portals of the selected facilities, and inspection activities Inspections included measurements (weight and dimensions), infrared profiling to monitoring traffic, x-ray imaging, and a limited number of visual inspections.[26] As planned, these inspections ended in May 2001.

Perimeters could either consist of attended stations or possibly be made "more minimal" through measures such as unattended radiation detection portals at strategic locations. Perimeter systems could be particularly attractive if only a handful of sites with smaller footprints require monitoring.[27] Using other sensors aimed at the detection of emissions from the plants are less meaningful as in the case of sites used for production or processing of nuclear materials. In general, no emissions can be expected from nuclear weapons deployment, production, storage, dismantlement sites.

Another possible approach to conduct inspections at sensitive nuclear facilities could be to have only the host access the site while the inspector follows the activities remotely, i.e., either from directly outside the facility or even from a distant location (possibly without traveling abroad at all). Communication between the host and the inspector could be established using various methods and technologies. A straightforward method would be a live video stream, but other technologies could also be considered.

The main advantage of such "secure virtual inspections" – a term first proposed by the Committee on International Security and Arms Control (CISAC) of the National Academy of Sciences – could be to avoid any access of inspectors to facilities that are considered particularly sensitive. Virtual inspections could be considered a variation of managed-access inspections, which have been demonstrated but are a necessarily complex undertaking. Managed access generally requires extensive preparations by the host party; in particular, the facility selected for inspection may have features or include items and activities that are irrelevant for the inspection task itself but may be considered sensitive for other reasons. In contrast, imagery transmitted during a virtual inspection would only include what is directly relevant for the task while essentially excluding everything else. In the case of a live video stream, key objective for the inspector would be to have confidence in the fact that the stream is live and that the transmitted data (i.e., the video feed) has not been tampered with. It may also be necessary to confirm that the video is being transmitted from the correct location. One way to address some of these challenges could be to include unique items or patterns in the (video) data.[28] These objects or patterns would only be known to the inspector and they could change in short time intervals, which could provide additional confidence in the integrity and "freshness" of the data and make replay attacks difficult or impossible.

This concept could have similar benefits for standard IAEA safeguards inspections. In particular, if such an approach was demonstrated and approved, certain routine procedures (for example, applying or verifying the integrity of seals) could be conducted using such an approach with inspectors monitoring relevant activities from Vienna.

A variation of such virtual inspections, where host and inspectors are at different locations, has been proposed as part of a possible denuclearization of North Korea,[29] but it could equally well be applied to other bilateral or multilateral arms control settings. Here, treaty accountable items would be jointly containerized and sealed – for example, using electronic seals – before the host takes them to secret locations for storage. The seal would be designed such that it displays unique, frequently changing alphanumeric codes (similar to an RSA SecurID device). From then on, inspectors could remotely request readout and transmission of these codes. For a properly designed system, the host party would only be able to provide the correct answers if the seal remains operational, confirming the state-of-health of the seal and the content of the respective container. Approaches like these could simplify verification of limits on containerized treaty-accountable items substantially.

Detecting Undeclared Facilities or Activities

This analysis focuses on verification objectives that can be achieved without onsite access to relevant declared sites. As such, detecting undeclared facilities is not a primary focus of our discussion. Still, some of the technologies and approaches discussed here have also or even mainly been used to detect previously unknown nuclear facilities.[30] Some prominent examples include facilities in Iran, Syria, and North Korea. We therefore briefly explore existing emerging capabilities of satellite imagery and wide-area environmental monitoring for detecting undeclared facilities.

Detecting undeclared uranium mines

The ability to remotely detect with high confidence undeclared uranium mines would be a useful capability not only to support nuclear disarmament verification but also to strengthen the existing nonproliferation regime. Declaring mining activities is already a part of the Additional Protocol, which requires states to provide the IAEA with "information specifying the location, operational status and the estimated annual production capacity of uranium mines" (INFICRC/540, Article 2). Satellite imagery can support related IAEA assessments and safeguards by providing independent information on the status of uranium mines, which are often located in remote and difficult-to-access areas. There have also been efforts to characterize known uranium mines, in particular open-pit mines, using hyperspectral satellite imagery, which can provide information on the elemental composition of the features in the scene,[31] i.e., such imagery can be used to identify ore pits, waste rock, tailings ponds, etc. Similar imaging techniques could be used to detect undeclared mines though other mining techniques, such as underground mines,[32] are more difficult to detect, especially when an adversary makes an effort to conceal them. In-situ recovery or in-situ leaching (ISL) dominates commercial uranium recovery today, and it may be particularly difficult to detect. ISL has very few surface signatures as no rock is ever brought to the surface and no tailings piles exist. Only injection and extraction wells are required. Undeclared ISL mining operations on a limited scale, large enough to support a small nuclear weapons program could be particularly difficult to detect. Undeclared uranium could also be produced as a byproduct of other mines, further complicating the detection effort.[33]

North Korea provides one important example as there have been some recent efforts to understand mining activities in the country, partly based on hyperspectral satellite imagery.[34] As part of this case study, imagery of the tailing piles from the only known uranium mine in North Korea, the Pyongsan uranium mining and milling complex, were used as a reference point for multispectral analysis. An algorithm then used the signature of the imagery from these known tailing-piles to look for similar signatures elsewhere in the country. In another part of the analysis, geological maps of North Korea were compared with similar maps of South Korea, where uranium-ore deposits are well documented. Findings from these complementary approaches can be combined to identify possible candidate sites for additional mines in the country. These locations could then be monitored more closely. While such an effort would be more difficult to implement in a larger country or geographical region, the use of state-of-the-art machine-learning algorithms combined with frequent-revisit satellite imagery shows significant potential in detecting undeclared mining activities.

Detecting undeclared fissile material production

Clandestine production of fissile materials could focus on production of plutonium, highly enriched uranium, or both. At a minimum an undeclared reprocessing or enrichment plant would be needed as we assume that declared facilities would be under safeguards. In the case of plutonium production and in addition to the secret reprocessing plant, a dedicated reactor would be required also, though abrupt diversion of existing spent fuel, even when under safeguards, to the secret reprocessing plant is of concern also.[35]

Nuclear reactors. The minimum power level of a nuclear reactor needed to support a small nuclear weapons program is on the order of 30 MW. Such a reactor, fueled with natural uranium, can produce about 8 kg of plutonium per year. The footprint of such a plant is sufficiently large to be easily recognizable in satellite imagery. The visual signatures of reactor sites are typically rather unique. Indeed, several historic cases exist where such a plant was discovered while under construction, even when efforts were made to conceal the nature of the construction project (see figure). Though there may be more elaborate deception efforts, such as underground construction, satellite imagery provides a powerful monitoring tool to detect undeclared reactors.

In addition to satellite imagery, antineutrino detection has been considered for "regional reactor discovery, exclusion, and monitoring" of nuclear reactors.[36] The fundamental constraint is size and cost of a system that would have the capability to detect an unknown reactor in the 30-MW range from a meaningful distance, i.e., from hundreds of kilometers away. Such long-range detection does not appear feasible "for the foreseeable future due to considerable physical and/or practical constraints."[37] There may be a possible role for the technology when deployed in a small region as part of a denuclearization agreement, when access to sites formerly part of a weapons program is severely constrained.

Uranium enrichment plants. Uranium enrichment plants, especially those based on gas-centrifuge technology, are notoriously difficult to detect. The footprint of these plant is rather small, and the visual signatures tend to be non-specific. Centrifuge enrichment plants require little electricity and no cooling infrastructure, which also facilitates underground construction. Similarly, emissions from centrifuge enrichment plants, in particular, atmospheric emissions of uranium gas or particles (UF_6, UO_2F_2) tend to be very small and quickly become non-detectable.[38] Here, it may be more promising to seek detection of an undeclared conversion plant, which produces the UF_6 feedstock needed for the enrichment process. Emission rates from conversion plants have been estimated to be 100–1000 larger than those from centrifuge enrichment plants.[39] Wide-area environmental monitoring could in principle have the potential to detect these signatures, especially when part of a regional (not global) monitoring effort. As in the case of reprocessing plants (discussed next), simple countermeasures exist to make WAEM much more challenging; for example, high-efficiency particulate air (HEPA) filters could reduce plant emissions by several orders of magnitude; similarly, an undeclared conversion or enrichment plant could be located close to a larger declared plant. Overall, the ability to detect undeclared enrichment plants remains a major challenge for verification of nuclear arms control and disarmament. Given that most weapon states have fissile-material stockpiles that far exceed their requirements, even based on their current warhead stockpiles, new production of fissile materials may not be considered a major concern for the foreseeable future.

The Al Kibar site (35.708 N, 39.833 E) in Syria in August 2007, shortly before it was destroyed by Israeli aircraft. The construction of an undeclared plutonium production reactor had apparently been underway,[40] possibly with foreign assistance. *Credit: Google Earth.*

Reprocessing plants. Unlike in the case of uranium enrichment plants, plutonium separation from spent fuel at reprocessing plants creates a unique atmospheric signature. Dissolution of irradiated nuclear fuel inevitably leads to the release of radioactive fission products including some noble gases, which are typically emitted from the plant; among these, krypton-85 is a clear indicator of spent fuel reprocessing. The isotope has a half-life of 10.8 years and has been accumulating in the atmosphere since reprocessing started on a large scale in the 1950s. The fundamental challenge is to detect weak krypton-85 signatures from a small plant against the global background and, more importantly, the continual fluctuations in krypton levels due to emissions from large declared plants and current weather conditions. It is widely believed that a global krypton-85 monitoring network having enough stations to enable detection of emissions from a small, unknown reprocessing plant anywhere on the globe would be prohibitively expensive.[41] Moreover, with known weather conditions, emissions from a large plant could be used to obfuscate the signal from a smaller undeclared plant.

Detecting the reprocessing plant itself, perhaps even during construction, using satellite imagery has to be considered difficult. The footprint of such a plant could be very small and the visual signatures could be similar or identical to other industrial plants. The possibility of clandestine construction of such a "simple, quick processing plant" has been a concern since the 1970s.[42] Especially when combined with the scenario of abrupt diversion of spent fuel from a declared site, timely detection of such a plant using krypton emissions remains a verification challenge that is fundamentally difficult to address.

Detecting undeclared weapons production or storage sites

Detecting undeclared weapons production or storage sites is probably among the hardest verification challenges for nuclear disarmament. There are no good assumptions about where to look for possible sites and what signatures to look for. Facilities could be underground and would be nondescript except perhaps for a security perimeter. In any event, a non-compliant party is likely to make every effort to make remote detection of such a site difficult, especially in a "timely" manner.

Satellite imagery may be the most viable monitoring technology available to international organizations for the task of detecting such sites. Governments may be able to access or acquire additional intelligence, in particular signal and human intelligence (SIGINT and HUMINT), which we do not consider here. Such original intelligence would enable closer monitoring of a candidate site with reconnaissance satellites. Once a site has been flagged for further examination, an archive of historic satellite imagery of the same location could be used to reconstruct the history of the site after the fact.

When no prior information about possibly suspect locations is available, the task becomes much more difficult. Given the sheer quantity of satellite imagery produced today, human analysts can no longer process this imagery in its entirety, and machine-learning techniques will become increasingly important in analyzing the data and flagging scenes for further examination and human review. There are already some case studies where machine-learning techniques have been successfully used to identify sites with national-security relevance.[43] In general, machine-learning algorithms require large amounts of training data in order to perform well. This is a particular challenge for the task at hand. Few warhead storage sites exist worldwide and there are no obvious unique visual features that could play a role in the training phase of the algorithm to answer the question of what makes a warhead storage site.

Conclusion and Outlook

> *"On-site inspection has been vastly overrated in the history of arms control."*
>
> *Allan Krass, 1985*

Onsite inspections are usually considered as a final, decisive measure in nuclear verification, both for NPT safeguards, for a possible verification of the CTBT, and for existing arms control agreements including New START. Onsite inspections of declared nuclear facilities are particularly well established in IAEA safeguards, with tailored approaches for different types of facilities. With a view to future disarmament agreements, it is safe to assume that onsite inspections will continue to play an important role. Notably, onsite inspections are not particularly controversial when inspected plants are operated for peaceful purposes, for example, as part of a fissile material (cutoff) treaty.

In the broader context of nuclear disarmament verification, onsite inspections can also be effective for nuclear weapons deployment, production, storage, and dismantlement sites. Past and ongoing nuclear disarmament verification initiatives such as the International Partnership for Nuclear Disarmament Verification (IPNDV)[44] and the Quad Nuclear Verification Partnership (QUAD)[45] have focused on how to develop and implement approaches and techniques for these scenarios. There might be, however, some room for complementing or minimizing the role of onsite inspections by applying appropriate remote and standoff monitoring technologies and approaches, as presented in this chapter.

Satellite imagery has historically played an important role in arms control verification, and its potential is likely to grow further in coming years. This will be partly due to dramatically increased coverage, now often allowing multiple revisits of the same site per day. At the same time, the growing interest in satellite-based synthetic aperture radar (SAR) sensors will make earth observation more robust against unfavorable conditions, including cloud coverage or even some deception efforts. One important mission of satellite imagery has traditionally been military reconnaissance and the search for undeclared (nuclear) facilities, where satellites can play a role in detecting undeclared uranium mines, fissile material production, and possibly even weapons deployment, production, or storage sites.

In addition, satellite imagery can support verification missions at declared nuclear sites. In fact, satellites have played a central role in verifying key provisions of the SALT and START agreements, which has minimized the need for onsite inspections. More recently, satellites have also started to play a limited role for IAEA safeguards, where imagery can be used, in particular, to detect or monitor changes at safeguarded sites, which could then inform decisions about future onsite inspections. Beyond that, and relevant for arms control and disarmament verification, satellite imagery could be used to confirm the shut-down status of fissile-material production facilities or other sites formerly associated with a weapons program.

Satellite imagery as a verification technology also faces some fundamental challenges, however. Among them are equitable access to imagery, trust in the authenticity of the data, and the resources and capabilities to analyze the data, which given the volume of imagery will have to rely increasingly on machine-learning techniques. Today, only very few states or organizations have these expertise and capabilities, and research and training efforts could usefully focus on how these capabilities can be guaranteed for all relevant stakeholders so that satellite imagery can unfold its true potential as a verification technology. If the area of interest is not accessible on the ground, satellite imagery represents one of the few opportunities to gather almost real-time data over the area.

Wide-area environmental monitoring has been considered for more than thirty years as a technique to complement location-specific environment monitoring ("swipe sampling"), which has been part of the approved IAEA safeguards procedures since the late 1990s. Several recent advances in sensor technologies and platforms combined with advanced modeling capabilities and data analytics have further increased the potential of the technique. Still, the deployment of monitoring systems with global coverage for detection of undeclared activities such as spent fuel reprocessing or uranium enrichment remains impractical. WAEM may have more potential in a regional context.

The potential role of wide-area environmental monitoring for declared facilities is more limited. On one hand, environmental monitoring becomes much easier as the standoff to the emitter is reduced, for example, when sensors are placed at the site boundary or even onsite. At the same time, however, it may then be more straightforward to use other technologies to accomplish the same verification objective without inspector access. Perhaps the greatest weakness of traditional concepts of wide-area environmental monitoring is the reliance on one particular sensor or signature, say, krypton-85 to detect reprocessing. Suppressing a single indicator can therefore provide an effective countermeasure. Recognizing this shortcoming, modern approaches therefore envision data-fusion from multiple sensor platforms. It's quite possible that this technique will make important contributions to national intelligence collection and analysis, but it's more difficult to see now international organizations could leverage these approaches for treaty verification purposes.

Perimeter portal continuous monitoring has received relatively little attention as a verification technology. This is likely to remain true in the case of IAEA safeguards. Perimeter monitoring has been and will remain logistically complex and relatively costly. Relevant technical developments over the past two decades have been less significant than in many other areas. It is unlikely that new technologies will emerge that could fundamentally change this situation. Perimeter monitoring appears most useful for sites where military activities are allowed to continue, which could include nuclear weapons deployment, production, storage, and dismantlement sites. The complexity and costs of perimeter monitoring increase with the areas and number of sites that are monitored. Perimeter systems could be particularly attractive if only few sites with small footprints require monitoring. Perimeter control could therefore be a viable option to consider for situations where these conditions are met. Overall, a better understanding of the potential of perimeter monitoring would be valuable and may deserve greater attention of the arms control verification community.

Nonconventional verification approaches combining different technologies offer another and perhaps even particularly promising strategy to complement or reduce the relevance of onsite inspections. Often, these approaches may not require major innovations, but they have so far not been used or combined for verification purposes. One example highlighted in the discussion are "secure virtual inspections," where inspectors follow an inspection remotely but can still draw meaningful conclusions about treaty compliance. Such approaches may benefit from recent advances in cryptography and secure transmission of digital data any may offer great potential in reducing the need for routine inspections.

Intrusive onsite inspections in nuclear arms control have been a feature and privilege since the 1990s, but only the United States and Russia have implemented them on a routine basis. Other potential parties have less experience and may be more reluctant to agree to such inspections, especially early on. It is therefore prudent to emphasize R&D and training efforts in directions that limit onsite inspections to what is deemed absolutely necessary, i.e., where a similar level of confidence cannot be achieved through other verification measures. This chapter has offered a few examples where remote and standoff monitoring technologies and approaches could help to minimize onsite inspection activities to some extent without compromising the effectiveness of verification.

Endnotes

1 J. Rutkowski and I.Niemeyer, “Remote Sensing Data Processing and Analysis Techniques for Nuclear Non-proliferation,” in I. Niemeyer, M. Dreicer, and G. Stein,eds., *Nuclear Non-proliferation and Arms Control Verification,* Springer, 2020; F. V. Pabian, G. Renda, R. Jungwirth, L. K. Kim, E. Wolfart, G. G. M. Cojazzi, and W. A. Janssens, “Commercial Satellite Imagery: An Evolving Tool in the Non-proliferation Verification and Monitoring Toolkit,” in I. Niemeyer, M. Dreicer, and G. Stein, eds., *Nuclear Non-proliferation and Arms Control Verification,* Springer, 2020.

2 *Handbook on the Design of Physical Protection Systems for Nuclear Material and Nuclear Facilities,* NST055, IAEA Nuclear Security Series, Draft Technical Guidance, International Atomic Energy Agency, August 2017.

3 A. Keskinen, J. Baute, M. Carey, J. Ng, and F. Ujkani, “Enhancing the Geospatial Exploitation System within the IAEA Department of Safeguards,” *Journal of Nuclear Materials Management* 46(3), 2018, pp. 60-67.

4 Rutkowski and Niemeyer, 2020, op. cit.

5 I. Niemeyer, “Data science in safeguards – opportunities and challenges,” *ESARDA 41st Annual Meeting, Symposium on Safeguards and Nuclear Material Management,* Stresa, Italy, May 2019.

6 J. Rutkowski, M. J. Canty and A. A. Nielsen, “Site Monitoring with Sentinel-1 Dual Polarization SAR Imagery Using Google Earth Engine,” *Journal of Nuclear Materials Management* 46 (3), 2018, pp. 48-59; Y. Feldman, M. Arno, C. Carrano, B. Ng and B. Chen, “Toward a Multimodal-Deep Learning Retrieval System for Monitoring Nuclear Proliferation Activities,” *Journal of Nuclear Materials Management* 46 (3), 2018, pp. 68-80; Z. N. Gastelum and T. M. Shead, “Inferring the Operational Status of Nuclear Facilities with Convolutional Neural Networks to Support International Safeguards Verification,” *Journal of Nuclear Materials Management,* 46 (3), 2018.

7 For a discussion of the possible use of location-specific environmental swipe sampling to verify a fissile material cutoff treaty, see A. Glaser and S. Bürger, “Verification of a Fissile Material Cutoff Treaty: The Case of Enrichment Facilities and the Role of Ultra-trace Level Isotope Ratio Analysis,” *Journal of Radioanalytical and Nuclear Chemistry,* 280 (1), 2009.

8 *INFCIRC/540*, International Atomic Energy Agency, Vienna, 1998, Article 9.

9 *Director General’s Report to the IAEA Board of Governors,* GOV/2784, International Atomic Energy Agency, Vienna, March 1995, §47.

10 *IAEA Use of Wide Area Environmental Sampling in the Detection of Undeclared Nuclear Activities,* STR-321, International Atomic Energy Agency, Vienna, August 1999; N. Wogman, *History of STR 321: IAEA Use of Wide Area Environmental Sampling in the Detection of Undeclared Nuclear Activities (1996–1998 Multi-country Effort),* PNNL-SA-75565, Pacific Northwest National Laboratory, November 2010.

11 R. Scott Kemp, “Source Terms for Routine UF_6 Emissions,” *Science & Global Security,* 18 (2), 2010.

12 D. Joshi, “Drone Technology Uses and Applications for Commercial, Industrial and Military Drones in 2020 and the Future,” *Business Insider,* December 18, 2019.

13 J. M. Brase, E. G. McKinzie, and J. J. Zucca, “Enhancing Verification with High-Performance Computing and Data Analytics,” in I. Niemeyer, M. Dreicer, and G. Stein (eds.), *Nuclear Non-proliferation and Arms Control Verification: Innovative Systems Concepts*, Springer, March 2020.

14 E. Banks, “ADAPD: Advanced Data Analytics for Proliferation Detection”, Presentation, LLNL-PRES-754931, *DSI Workshop*, August 2018; *ADAPD: Advanced Data Analytics for Proliferation Detection,* Lawrence Livermore National Laboratory. Available: *computing.llnl.gov/projects/adapd-advanced-data-analytics-proliferation-detection*.

15 L. Scheinman and M. Kratzer, *INF and IAEA: A Comparative Analysis of Verification Strategy,* LA-12350, Los Alamos National Laboratory, New Mexico, July 1992.

16 *PPPL Researchers Develop MINDS Anti-Terrorism Device,* PPPL Fact sheet, Princeton Plasma Physics Laboratory, March 2011.

17 B. K. Cogswell and P. Huber, “Detection of Breeding Blankets Using Antineutrinos,” *Science & Global Security,* 24 (2), 2016; C. Stewart, A. Abou-Jaoude, and A. Erickson, “Employing Antineutrino Detectors to Safeguard Future Nuclear Reactors from Diversions,” *Nature Communications,* 10, 2019.

18 M. E. Walker, *Reinventing International Nuclear Safeguards in the Centrifuge Enrichment Era,* PhD Thesis, Princeton, NJ, June 2018.

19 L. Eric Smith and A. R. Lebrun, “Design, Modeling and Viability Analysis of an Online Uranium Enrichment Monitor,” *2011 IEEE Nuclear Science Symposium Conference Record,* Valencia, Spain, 2011.

20 S. Aslam and R. J. Goldston, "Analysis of a UF_6 Thermal Mass Flow Meter," *60th Annual INMM Conference,* Palm Desert, CA, July 2019.

21 H. Kouts, *A Perimeter Safeguards System for Enrichment Plants,* U.S. Arms Control and Disarmament Agency and U.S. Atomic Energy Commission, November 1972; P. E. Fehlau and W. Chambers, *Perimeter Safeguards Techniques for Uranium-Enrichment Plants,* LA-8997-MS, Los Alamos National Laboratory, New Mexico, September 1981.

22 S. Johnson, *The Safeguards at Reprocessing Plants under a Fissile Material (Cutoff) Treaty,* IPFM Research Report, February 2009.

23 E. Ifft, "Verification Lessons Learned from the INF, START I, and New START Treaties," *55th Annual INMM Meeting,* Atlanta, Georgia, July 2014.

24 F. von Hippel, "Challenge Inspections at Military Nuclear Sites," Chapter 8 in *Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty,* Princeton, NJ, September 2008.

25 Scheinman and Kratzer note that "the initial idea of perimeter portal monitoring had been raised by the US as a means of enhancing capacity to monitor compliance with an agreement that would have involved residual levels of production rather than a production ban. When total prohibition was agreed the purpose of perimeter portal monitoring became problematic since the presence of even a single prohibited item anywhere would be a violation of INF" (Scheinman and Kratzer, 1992, p. 75).

26 J. P. Harahan, *On-site Inspections Under the INF Treaty,* U.S. Department of Defense, Washington, DC, 1993. See, in particular, Chapter 5 ("INF Continuous Portal Monitoring Inspections"), pp. 67–98.

27 T. Patton and A. Glaser, "Deferred Verification: The Role of New Verification Technologies and Approaches," *Nonproliferation Review,* 26 (3–4), 2019.

28 R. G. Johnston and J. S. Warner, "Unconventional Approaches to Chain of Custody and Verification," *51st Annual INMM Meeting,* Baltimore, Maryland, July 2010; R. Hughes, "Review and Redaction-Tolerant Image Verification Using Cryptographic Methods," *Science & Global Security,* forthcoming.

29 A. Glaser and Z. Mian, "Denuclearizing North Korea: A Verified, Phased Approach," *Science,* 361 (6406), September 7, 2018.

30 D. Albright, S. Burkhard, and A. Lach, "Commercial Satellite Imagery Analysis for Countering Nuclear Proliferation," *Annual Review of Earth and Planetary Sciences,* 46, 2018.

31 Q. S. B. Truong, G. A. Borstad, K. Staenz, R. Neville, and R. Leslie, et al., "Multispectral and Hyperspectral Imagery for Safeguards and Verification of Remote Uranium Mines," *44th Annual INMM Meeting,* Phoenix, AZ, July 2003; L. Sundaresan, S. Chandrashekar and B. Jasani, "Discriminating Uranium and Copper Mills Using Satellite Imagery," *Remote Sensing Applications: Society and Environment*, 5, 2017.

32 For a description of modern mining methods, see *www.cameco.com/businesses/mining-methods*.

33 R. S. Kemp, "On the Feasibility of Safeguarding Uranium Mines," *Nonproliferation Review,* 13 (2), July 2006.

34 F. Derby and S. Park, "Minesweeping," *Jane's Intelligence Review,* October 2019; S. Park, A. Puccioni, C. L. Tracy, E. Serbin and R. C. Ewing, "Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines," *Science & Global Security,* 28 (2), 2020.

35 See "Nuclear Power and Nuclear Disarmament," Chapter 8 in *Global Fissile Material Report 2009: A Path to Nuclear Disarmament,* International Panel on Fissile Materials, Princeton, NJ, October 2009.

36 I. Jovanovic and M. Foxe (co-chairs), *Regional Reactor Discovery, Exclusion, and Monitoring*, Factsheet, May 2020. Additional antineutrino factsheets available at *nutools.ornl.gov/fact-sheets*.

37 A. Bernstein, N. Bowden, B. L. Goldblum, P. Huber, I. Jovanovic and J. Mattingly, "Colloquium: Neutrino Detectors as Tools for Nuclear Security," *Review of Modern Physics,* 92 (011003), March 2020.

38 R. S. Kemp, "Environmental Detection of Clandestine Nuclear Weapon Programs," *Annual Review of Earth and Planetary Sciences,* 44, 2016.

39 Kemp, 2010, *op. cit.*

40 A 2008 IAEA report concluded: "While it cannot be excluded that the building in question was intended for non-nuclear use, the features of the building, [...] along with the connectivity of the site to adequate pumping capacity of cooling water, are similar to what may be found in connection with a reactor site;" *Implementation of the NPT Safeguards Agreement in the Syrian Arab Republic,* Report by the Director General, GOV/2008/60, International Atomic Energy Agency, Vienna, November 19, 2008.

41 M. Schöppner and A. Glaser, "Present and Future Potential of Krypton-85 for the Detection of Clandestine Reprocessing Plants for Treaty Verification," *Journal of Environmental Radioactivity,* 162–163, October 2016.

42 D. E. Ferguson, *Simple, Quick Processing Plant,* Intra-Laboratory Correspondence, Oak Ridge National Laboratory, August 1977. Available: *www.ipfmlibrary.org/fer77.pdf*.

43 For example, deep convolutional neural networks have been used to search for and detect surface-to-air-missile sites in China; see R. A. Marcum, C. H. Davis, G. J. Scott and T. W. Nivin, "Rapid Broad Area Search and Detection of Chinese Surface-to-Air Missile Sites Using Deep Convolutional Neural Networks," *Journal of Applied Remote Sensing*, 11 (4), October–December 2017. It is worth pointing out, however, that these sites have rather distinct visual features and that the "monitored party" made no attempts to obfuscate these features.

44 *www.ipndv.org*.

45 *quad-nvp.info*.

5. Weapons Production and Research

MORITZ KÜTT

ABSTRACT. *On the way to complete and irreversible nuclear disarmament, verification efforts will likely include the elimination of the "nuclear enterprise," the facilities for research and development, component production, and nuclear weapon assembly. Production facilities are used for manufacturing pits and secondaries out of fissile material, as well as neutron generators, tritium components, detonators, shaped conventional explosives, or arming, fuzing and firing mechanisms. Research facilities typically carry out extensive simulations and experiments. Four key verification objectives create confidence in successful elimination or conversion: Ensuring the termination of facility operation, confirming facility elimination, certifying facility conversion, and confirming the absence of undeclared facilities. The last objective is applicable also to non-nuclear weapon states. This chapter will discuss various verification technologies to address the four objectives. These include on-site inspections, perimeter control, continuous remote monitoring of sites, and the detection of relevant process materials through local and wide-area environmental sampling. Several nuclear weapon states have – corresponding to reductions of their nuclear arsenals – already eliminated or converted some facilities. Non-intrusive efforts could begin immediately at those facilities. The verification efforts will become more intrusive when additional, currently active, facilities are included.*

Introduction

Complete and irreversible nuclear disarmament goes beyond dismantling nuclear warheads. It will also require the disposition of fissile materials recovered from these weapons and the elimination or conversion of all nuclear weapon production capabilities. The elimination and conversion processes include facilities to assemble and disassemble weapons, manufacture components, as well as research, development and testing infrastructure. Monitoring and verification of the elimination and conversion processes provides confidence that no new nuclear weapons are developed or produced.

Public knowledge of weapon production processes is incomplete, as many aspects are kept secret by nuclear weapon states. Nevertheless, publicly available information provided by independent experts as well as from official government releases is sufficient to start discussing verification options for nuclear weapon production capabilities. In the future, states could discuss which additional information required for verification purposes could be released without creating risks for individual states' security.

In the following, the production and research capabilities will be summarized as "nuclear enterprise," a term recently used by the International Partnership on Disarmament Verification (IPNDV).[1] In Working Papers submitted to the 2018 and 2019 meetings of the United Nations Group of Governmental Experts on nuclear disarmament verification, authors used the term "weapon production capabilities"[2] or described production and research as part of the "upstream phase" of a nuclear weapon life cycle.[3] The "Model Nuclear Weapons Convention," a proposal by non-governmental organizations, called for the decommissioning or conversion of "nuclear weapons facilities", defined as "any facility for the design, research, development, testing, production, storage, assembly, maintenance, modification, deployment, delivery, command, or control."[4] In the Treaty on the Prohibition of Nuclear Weapons (TPNW), which entered into force in January 2021, the facilities are summarized as the "Nuclear Weapons Programme" of a state. For nuclear weapon states, the treaty requires the complete elimination or conversion of these programs.[5]

Several nuclear weapon states have already eliminated or converted facilities in the past following reductions of their nuclear arsenals. Early and low intrusive verification efforts could focus on those facilities. They could enable states to test and improve technologies and procedures and train inspectors for more intrusive measures. Verification could, over time, be expanded to include additional facilities. Sites used for the process of dismantlement will handle nuclear weapons until complete disarmament is achieved.[6] As such, they will likely be the last to be eliminated or converted. For those facilities, verification efforts could be more intrusive to ensure that any weapon component present is only there because of dismantlement efforts.

The issue of verifying the elimination or conversion of the nuclear enterprise is a problem that has received limited scholarly attention so far. At the beginning of this millennium, the issue of monitoring the nuclear weapon complex was discussed in a larger report by the British Atomic Weapons Establishment on verification challenges of future arms control agreements.[7] In an article in 2002, James Doyle and Oleg Bukharin elaborated on potential verification technologies to verify the shutdown and conversion of excess weapon production capabilities in Russia and the United States.[8] More recently, the work of IPNDV expanded its focus from verifying the steps required for warhead dismantlement to also address the issue more broadly.[9] Other scholarly work includes a report by the Carnegie Endowment for International Peace on a potential "firewall" against proliferation. The report discusses key elements of the nuclear enterprise, but takes a perspective focusing mostly on how to prevent additional states from gaining such capabilities.[10] An article by Tamara Patton proposes an international monitoring system for the TPNW, based on past experiences of detecting proliferation attempts mostly in non-nuclear weapon states.[11]

This chapter is a new attempt to provide technical and procedural details for verifying the elimination or conversion of the nuclear enterprise. It is based on information from the previously listed works, and publicly available information. The detailed requirements for the elimination or conversion of a nuclear enterprise are currently not part of any international agreement.[12] As such, it is the goal of this chapter to provide a menu of verification options. States could decide in the future to require only some of these options, depending on the monitoring targets set out in future agreements.

Weapon production capabilities also require states to produce and store fissile material for nuclear weapons, i.e., plutonium and highly enriched uranium. This issue is not discussed in this chapter but is covered in the chapter *Fissile Material Stocks and Production*. Through the International Atomic Energy Agency, the international community has long-standing expertise in monitoring the civilian use of fissile material-related facilities in non-nuclear weapon states through its extensive safeguards network. Voluntary safeguards agreements exist for nuclear weapon states. An extension to all fissile material-related facilities could, for example, be mandated by a Fissile Material (Cutoff) Treaty and subsequent verification measures. Experience from fissile material monitoring could be transferred to verification efforts discussed here.

In addition to weapon production, states need research infrastructure and production capability to produce delivery systems for nuclear weapons. Delivery systems have been addressed in prior and current arms control agreements (e.g. START, New START). In some proposals, they are included in definitions of the nuclear enterprise. For the purpose of this chapter, delivery system research and production is excluded – only facilities directly involved in nuclear weapons production will be addressed.

The next section proceeds by outlining different aspects of the nuclear enterprise in more detail. This is followed by a section defining four key verification objectives that need to be addressed to verify the elimination or conversion of the nuclear enterprise. For each of these verification objectives, existing and future verification technologies will be presented in the final section of this chapter.

The Nuclear Enterprise

Depending on the size of a country's nuclear arsenal, the size of the nuclear enterprise varies. It ranges from few, central facilities capable to provide all components and to assemble weapons, to a highly diversified nuclear weapons complex with task division among multiple organizations and sites at various locations in the country.

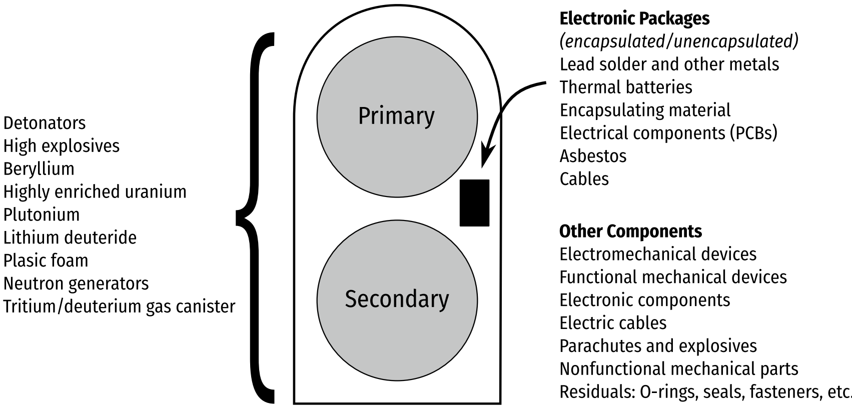
During the early phases of weapon research and production, the facilities of the nuclear enterprise were kept secret by all states. Today, some information has been made public by the states themselves. Additional information is provided by independent experts. The most complete picture of nuclear weapon facilities is available for the United States. Public documents discuss various elements of the nuclear enterprise.[13] While most other states have smaller nuclear weapon programs, it can be assumed that the main elements and processes are very similar.[14] For the United Kingdom, a 2018 report listed key facilities of the "Defence Nuclear Enterprise."[15] Older references compiled by the non-governmental organization Natural Resources Defense Council also provide comprehensive summaries of the nuclear enterprises in Russia,[16] France and China.[17] The elimination and conversion of past production facilities has been ongoing, in fact for several decades. A comprehensive review of specific facilities is beyond the scope of this article, which focuses on potential verification approaches and technologies in a more general manner.

Components of a nuclear weapon

The necessary facilities to produce modern thermonuclear weapons can be explained along the list of components. The weapon consists of a primary and secondary component. The primary initiates the explosion, relying on nuclear fission reactions to provide the energy for fission and fusion reactions in the secondary.

The figure below shows a typical list of materials and components, based on an official United States government report. It includes highly enriched uranium and plutonium (fissile materials), other materials including beryllium, lithium deuteride, depleted uranium, plastic foam and high explosives, key components like detonators, neutron generators and tritium containers as well as a longer list of electrical and mechanical components.

The fissile material is the key element for both primary and secondary. Besides producing the material (covered in the chapter *Fissile Material Stocks and Production*), it is necessary to manufacture special shapes. The primary is often a hollow sphere of fissile material, the so-called pit.[18] Fissile materials are heavy metals and difficult to handle. Especially plutonium is highly radioactive and also toxic. Hence, special protective measures like gloveboxes or radioactive hot-cells with remote operation capabilities are required. The process also requires complex material science information to ensure the chemical stability of the pits. Plutonium pits are commonly stabilized as an alloy with gallium.[19] The complexity of pit production, even today, is made apparent by the fact that the United States plans to increase its production capability but is struggling to do so.[20] The secondary also contains lithium-deuteride as fuel for the fusion reaction. Only the isotope lithium-6 is relevant for nuclear weapons. As it is only present in small fractions in natural lithium, enriched lithium is used instead.



List of nuclear weapon components. Image adapted from: *Dismantling the Bomb and Managing the Nuclear Materials*, United States Office of Technology Assessment, Washington, D.C., 1993, p. 37.

In the primary, the pit is surrounded by additional materials. All warheads need a layer of conventional high-explosives, specifically shaped to allow for an implosive pressure wave which compresses the pit to achieve criticality. Various types of conventional explosives are used. Combining the explosive with the inner sphere is a delicate process. Weapon states have used special assembly cells ("gravel gerties" in the United States, "towers" in Russia[21]), which are built to withstand unintentional conventional explosions. For modern designs, weapon states aim at using insensitive explosives, i.e., materials unlikely to explode if mechanically altered or exposed to heat. Such explosives reduce the need for gravel gerties, but assembly and disassembly will still take place in blast-proof bays.[22] Facilities that handle conventional explosives also have additional reinforced storage sites.[23]

The explosives are ignited using special detonators, which all need to fire in a very limited time window. Most detonators are "explosive bridgewire detonators", where a small wire explodes due to a high current. In the United States, modernization efforts today include exploding foil generators, and research work is ongoing for laser-driven detonators.[24]

Neutron generators support the start of the fission chain reaction in a nuclear weapon. Early neutron generators consisted of radioactive alpha emitters (e.g. polonium), and a second material absorbing these particles, emitting neutrons in turn (e.g. beryllium).[25] Newer developments are electric neutron generators, which use an electric potential to accelerate deuterium onto tritium targets. Electric potentials come from ferroelectric generators or batteries.[26] Manufacturing sites need to handle deuterium, tritium, or other specific elements like polonium. In addition, electric neutron generators likely need clean room production facilities,[27] ferroelectric generators need explosive handling facilities.[28]

To achieve a higher, and perhaps more predictable, yield of the primary ("boosting"), tritium is injected into the pit prior to the explosion. As it has a half-life of only 12.3 years, it needs to be regularly replaced. The tritium reservoir must be replenished multiple times during the lifetime of a nuclear weapon. The tritium production process includes production in nuclear reactors, separation of tritium from special targets, and facilities to fill and refill tritium containers.[29]

Weapon manufacturing activities at all levels have to be supported by research and development.[30] In addition, critical tests for new weapon designs commonly require hydrodynamic experiments and tests of the nuclear weapons themselves. All current nuclear weapon states have conducted nuclear weapon test explosions.[31] For those tests, often specific facilities are prepared, including underground tunnels and cavities. After testing, radioactive remnants of explosions can be detected during on-site inspections.[32]

Most nuclear weapon enterprises also possess significant simulation capabilities. These provide ways to validate designs in the absence of tests. Simulation capabilities are supported by high-performance computing. An indication of the importance of high-performance computing for nuclear weapon enterprises can be seen by the fact that as of November 2020, five out of the twenty fastest supercomputers in the world are operated by weapon laboratories of the United States Department of Energy.[33]

Elimination activities in the past

The international community has some prior experience in identifying potential nuclear enterprises and monitoring their elimination. South Africa owned a small number of nuclear weapons during the 1980s. It joined the Nuclear Non-Proliferation Treaty in 1991, but only in 1993 publicly disclosed a prior weapon program which had already been dismantled. Subsequently, the IAEA intensified inspection visits to the country to verify the successful elimination. It concluded that the program was terminated and eliminated. This is the only case where the elimination of a successful nuclear weapon program took place.[34]

Further experience was gained on multiple occasions by inspecting non-nuclear weapon states suspected of violating their nonproliferation obligations. Inspections targeted facilities and observed indicators of the various weapon production steps outlined above.

In Iraq, clandestine weapon activities were discovered during the 1991 Gulf War. The United Nations Security Council tasked the IAEA in 1991 to verify the elimination of Iraq's nuclear enterprise and monitor that it was not re-established. The Agency's Iraq Nuclear Verification Office (INVO) coordinated a large number of inspections, including visits to facilities for radiochemistry experiments, separation of plutonium in hot-cells, uranium metallurgy, high explosive production, handling and experiments, and production facilities for detonators. Under the auspices of the IAEA, these facilities were destroyed.[35] To avoid reconstitution, Iraq was prohibited items from a special list provided by the Agency or allowed use only under certain controls. The list included, for example a prohibition to operate "Facilities or plants for the production, recovery, extraction, concentration or handling of tritium," and required Iraq to declare all use of electrically driven explosive detonators, including exploding bridge wire, slapper or exploding foil initiators.[36] Over more than a decade of inspections, INVO acquired significant expertise monitoring a nuclear enterprise – this expertise should support future efforts of nuclear enterprise elimination and conversion efforts.

In Libya, which was also suspected of having a clandestine nuclear weapons program, extensive inspections were carried out by the IAEA in 2003 and 2004. Their goal was to verify that Libya eliminated materials, equipment and programs relevant for nuclear weapon production. During the inspections, the Agency visited a number of locations that could have supported the weapon program. These included, among other facilities, installations capable of handling high explosives and metal casting, and those relevant for missile warhead design and manufacturing. The detailed list of facilities has been published by the IAEA in Reports by its Director General.[37] Experiences in Iraq and Libya could support future verification efforts for the elimination and conversion of nuclear weapon enterprises.

Verification Objectives

The verification of the elimination or conversion of the nuclear enterprise can be separated into four separate verification objectives: Ensuring termination of operation, confirming elimination, certifying conversion, and the ability to detect undeclared facilities. The fourth objective might also be applied to non-nuclear weapon states to ensure equitable treatment under future agreements.

Ensuring termination of operation of nuclear enterprise facilities is relevant during the time period from the beginning of an international agreement banning their use up to the time when a facility is eliminated or converted to civilian purposes. Thorough verification of termination of operation demonstrates to the international community that no further weapon production is intended. In this phase, facilities remain, in principle, operational. States could opt for a prolonged standby period as an initial confidence building measure prior to further disarmament steps.

The elimination process of a facility can start any time after operations have stopped. It will likely include clean-up activities of environmental pollutants accrued over the operation. Potential delays might be due to the above-mentioned confidence-building period, the time required for radioactive remnants to decay to safe dose levels or the need to develop sustainable methods for the dismantlement process. Ideally, the elimination process would be irreversible. The verification objective for this phase is to ensure that the decommissioning proceeds continuously towards a final brownfield or greenfield state.

Instead of elimination, nuclear weapon states could also decide to reuse facilities for other purposes. In that case, the international community would likely require that such a conversion leads to either civilian-only use or usage clearly distinct from nuclear weapon production. Here, the verification objective would be to certify that the conversion is successful, and the newly declared use is the only possible utilization of a facility. Future agreements could proscribe that verification activities would end after conversion has been certified.

Conversion is a relevant option, and has been pursued already in the past. An example is the Pinellas Plant in Largo, Florida. During the Cold War, the facility produced weapon components, including neutron generators.[38] After ceasing operation for the nuclear enterprise, the Pinellas Plant has been gradually transformed into a site to host high technology companies and is now called the Young-Rainey STAR Center.[39] Since the beginning of the conversion, the site housed a large variety of companies, including military contractors. Therefore, certification of conversion to activities unrelated to nuclear weapon programs at such sites likely will be a challenging task.

The most difficult verification objective is the ability to detect undeclared facilities with high confidence. The previous three objectives all dealt with known facilities, typically after initial declarations. A state choosing to break out of a nuclear disarmament agreement could choose to do so using clandestine facilities for weapon production. This verification objective aims at detecting such facilities in a time that is shorter than the potential break-out time. There is no fundamental difference between former nuclear weapon states and non-nuclear weapon states with regard to this objective. Whether related verification activities were to be carried out in all states is a political decision to be determined during the negotiations of future disarmament agreements.

Verification activities for all four objectives can be carried out at different levels of intrusiveness. The first three objectives could address facilities that have already halted nuclear weapon production in the past. More intrusive measures would include active facilities from the moment production is terminated onward. Likely, some form of monitoring will also be required when a facility is in use for dismantlement purposes only. In that case, not only the dismantlement should be verified, but the facility needs to be monitored for clandestine parallel weapon production capabilities. The intrusiveness for the detection of undeclared facilities ranges from using only publicly available remote sensing data to comprehensive on-site inspections in facilities suspected to be part of a nuclear enterprise.

Verification Technologies

In the following, a variety of verification technologies will be discussed. It should be noted that not all of these technologies need to be used together for successful verification. Rather, technology selection will depend on the required level of confidence, the permissible intrusiveness as well as the resources available. The table below shows an overview of potential verification technologies.

Verifying termination of operation of facilities, confirming their elimination or certifying their conversion would all be conducted at declared sites. The scope of declarations depends on an agreed definition of the nuclear weapon enterprise. It should include information whether states are planning to eliminate or convert certain installations. Declarations for facility conversion should include the future intended purpose of the facilities. Initial declarations could also be supported by making available historical operation records to inspectors. Such a "nuclear archaeology" approach has already been proposed for fissile material production.[40]

Related to declarations, a first potential monitoring activity for all three objectives are baseline inspections, or "familiarization visits." In these inspections, inspectors would visit the declared sites to ensure that the declarations adequately reflect the purpose and status of facilities. They could potentially include a list of declared essential equipment that could be confirmed as well. Baseline inspections were conducted in the past, for example, under the INF Treaty.[41] Such inspections can be very intrusive for facilities undergoing termination of operation, less intrusive for facilities already converted to civilian use, and least intrusive for sites of former facilities that were already eliminated.

Verification objective	Existing experience	Less intrusive verification measures	More intrusive verification measures
Termination of operation	INF Treaty, IAEA missions in Iraq, Libya and South Africa	Satellite imagery, overflights, perimeter monitoring, environmental sampling, analysis of historical documents	Short-notice on-site inspections, seals, on-premise remote monitoring
Confirming elimination	INF Treaty, IAEA missions in Iraq, Libya and South Africa, recently: North Korean test-site demolition, START (delivery vehicles)	(Remotely) monitoring destruction, analysis of historical documents	On-site inspections (former sites), destruction with active help of inspectors
Certifying conversion	IAEA mission in South Africa	Analysis of planning documents	On-site inspections
Detecting undeclared facilities	IAEA Additional Protocol	Satellite imagery, overflights, wide area environmental sampling	On-site inspections at suspect facilities

Verification objectives, existing experience from international treaties and other events, selected verification measures.

Termination of operation & confirming elimination

To verify that facilities terminated their operation, several measures are possible. The facility could be monitored from the outside, including all traffic going in and out. Portal and perimeter continuous monitoring methods were used as part of the inspections under the INF Treaty regime. For example, the United States operated sensors and imaging devices to monitor all rail-cars leaving the Votkinsk facility. In addition to measuring masses and dimensions, the monitors also provided x-ray capabilities to ensure that only permitted missiles left the facility.[42] Portal monitors can also discover radioactive materials inside of cargo, an efficient way to search for nuclear components leaving, as well as entering facilities. In principle, no nuclear component should leave or enter a facility not in operation. The technology is extensively used at border controls, however challenges remain with regard to the weakly-radioactive uranium and small amounts.[43] Some state-of-the-art technologies use cosmic rays, which can improve detectability of heavy metals like uranium but need measurement times in the order of several hours.[44] Smaller components, especially when hidden in larger cargo, are difficult to detect in current setups. However, this can change if the allowed object size is reduced and measurement times are extended. While such optimization is hardly possible in high throughput border controls, it can be much easier implemented in facilities where operation is declared to be terminated.

Additional outside monitoring opportunities exist from further away. During the Cold War, satellite reconnaissance was left to states and only to be used on very valuable targets. Today, resolution and image availability is constantly increasing. Not only states, but more and more also commercial operators launch new satellite formations. The revisit frequency increases, so satellites could support such monitoring activities.[45] In principle, aircraft overflights could replace data gathered through satellites or be used alongside with it. The Open Skies Treaty could provide a blueprint for negotiations on procedures and allowed technologies.[46]

Moving from outside the facility to monitoring activities inside, the most obvious approaches are containment and surveillance measures. These are equivalent to those commonly used by the IAEA for fissile material safeguards. Seals combined with further inspections can show that equipment has not been used or that certain facility parts have not been accessed. Sealing technology ranges from simple metal cup seals, which have been used for approx. 50 years, to complex electronic seals that can transmit their status remotely.[47] Cameras can either record locally, and – enclosed in tamper-proof casings – store the recording until the next inspection or be able to continuously transmit data to a remote location.[48]

IAEA containment and surveillance activities are focused on fissile material, and take place nearly exclusively in non-nuclear weapon states. For verifying the termination of operation of facilities of nuclear enterprises, adaptations will be necessary. The adapted activities need to cover other materials, e.g. high explosives, if those remain after termination of operation. And they need to be employed in nuclear weapon states, which might create additional requirements to protect sensitive information.

In the context of extensive laboratory-to-laboratory exchanges in the 1990s, United States and Russian weapon laboratories developed extensive multi-sensor systems to monitor storage sites of nuclear weapons, for example the Magazine Transparency System[49] or the Material Monitoring System.[50] These systems use a combination of cameras and other sensors, e.g. motion detection sensors, or magnetic field sensors to ensure the non-movement of a blanket equipped with magnets. These combinations were deemed more effective than individual technologies. Although the systems were developed for a slightly different goal, the technology could be adapted to support verification of the termination of operation in the nuclear enterprise. Independent of the system used, states would need to agree whether data transfer out of facilities would be allowed for remote collection, or if only on-site recording combined with inspections is permissible.

The production process of nuclear weapons makes use of a large number of special materials, including tritium, lithium, beryllium, gallium, high explosives, plutonium, and uranium. Once a facility terminates operation, it could be required to be cleaned of those materials. Afterwards, the materials could become indicators that operations have been resumed.

Radiation detectors for neutron and gamma emissions are potential on-site monitoring measures to detect the radioactive materials. This can be done during on-site inspections. Shielding materials might prevent such detection, potentially allowing the host party to hide components. Additional analysis is necessary to determine whether shielding can be detected through other means, or if objects and materials in former weapon facilities can be restricted to avoid the risk of covert shielding.

Small traces of the above listed materials can be detected using mass spectrometry. As the detection systems are relatively large, it is necessary to collect samples potentially containing these materials and conduct analyses at centralized laboratories. Inside of facilities, a common method is to collect surface swipe samples for later analyses. Potentially, environmental sampling could also be used outside of facilities. Many have gaseous or vapor emissions, liquid inlets in local water bodies and rivers or particulate depositions.[51] Future research is required to study the feasibility of such environmental samples for detecting the materials relevant in the nuclear enterprise.

Because past allowed operations might have led to prior depositions, initial background measurements of continuous sampling operations might be required. This is true both for radiation measurements as well as trace sample collections. Some of the materials are used in large quantities in other industrial processes. Lithium is used for batteries of mobile devices and electric vehicles. However, in that case the material is not enriched, as it would be for nuclear weapons purposes. Gallium plays an important role as a substrate for semi-conductors. However, states could agree that such materials were to be banned on sites of former weapon production facilities. This would allow the detection of covert operations there.

To confirm the elimination of facilities, an option providing high confidence is to have inspectors present at a site during demolition. For example, the DPRK invited international journalists to be present during the destruction of its nuclear test site in 2018.[52] Similarly, in the 1990s, IAEA inspectors observed on site how equipment and materials in Iraq were destroyed or rendered harmless.[53] Remote monitoring methods as described above, for example satellite imagery or local cameras, can support monitoring during the elimination of facilities, or to ensure that eliminated facilities are not rebuilt.

Certifying conversion

The initial step of the certification of conversion is to define what constitutes a converted facility. Whereas for fissile material production converted facilities will likely be continuously covered by IAEA safeguards, this is not necessarily the case for other facilities in the nuclear enterprise. Here, the conversion likely results in a facility producing or researching goods that are already produced outside of the nuclear enterprise, even in non-nuclear weapon states, and to which no inspection regime applies.

The definition of a converted facility is in part a political process. States have to decide from which moment on they have high confidence that no future weapon-related activities will take place anymore. In respective negotiations several aspects should be taken into account. First, it is likely that the local workforce will maintain knowledge and skills related to weapon component production for some time after the conversion. The certification needs to ensure that such capacities do not support fast re-conversions of facilities. This is also a key difference to non-nuclear weapon states, where no such experience is to be expected.[54] Second, the definition might exclude certain future use cases. This could, for example, ban military uses, or military contractors from operating a converted facility, or the use of explosives on these sites. Even civilian uses could be limited. The definition could for example allow for open research and educational purposes only. An example for the latter is the conversion of the K-25 uranium enrichment plant in the United States. On its site, there is now a history center run by the United States National Park Service, open to visitors from around the world.[55] Lastly, it is important to note that the decision to convert a facility might also be rejected by other states. If states do not have sufficient confidence in a conversion, facilities could be eliminated instead.

The international community has only limited experience with certifying conversion. During the inspections in Iraq in the 1990s, most facilities of the Iraqi nuclear weapon program were demolished, most equipment was destroyed.[56] In South Africa, however, it was one of the goals of IAEA inspections to show "that all laboratory and engineering facilities involved in the programme had been fully decommissioned and abandoned or converted to commercial non-nuclear usage or peaceful nuclear usage."[57] As part of the inspections, it was confirmed that some machine tools had been made available for commercial non-nuclear applications. These experiences could support the development of certification procedures for nuclear enterprise facility conversion.

Verification approaches to be used to certify the conversion of facilities are twofold. Initially, states should outline their plans for the conversion. Inspecting parties could analyze these documents for plausibility, and potentially check against lists of prohibited pieces of equipment. Later, during the conversion, on-site inspections can ensure that the process proceeds as planned. A special, longer inspection could be the "certification visit" at the end of the conversion. This visit would also mark the end of the verification activity. Afterwards, the facilities would be treated like any other facility outside of the nuclear enterprise. They would be subject to any verification measure agreed upon to detect clandestine activities as discussed in the following subsection.

An alternative to this verification objective could be continued monitoring as long as the facility remains in (any) operation to ensure that no new nuclear-weapon related activities take place. This would introduce monitoring to facilities which under other circumstances, i.e., when never part of a nuclear enterprise, are not monitored. For example, a facility in a nuclear weapon state could be converted to produce conventional ordnance. Such facilities exist outside of the nuclear enterprise, and also in non-nuclear weapon states. As an expansion of monitoring activities to all those facilities will come with high cost and resource requirements, continued monitoring must be weighed against the potential gain in confidence of absence of weapon activities both in former nuclear weapon states as well as in all other states.

Of particular interest for continued monitoring could be former weapon research facilities, as those can be repurposed for new tasks relatively easily, but similarly returned to its original purpose.[58] In addition to physical laboratories, nuclear enterprises often operate significant computing centers for simulation and modeling.[59] Because of the ability to rapidly reuse them, voluntary transparency measures for research facilities are important confidence-building steps. Such measures could include, for example, a shift to exclusively conduct public, unclassified research available through open access publishing procedures.[60] Additionally, a program to hire an increased number of foreign nationals as scientists and staff in all departments would demonstrate that research does not concern matters of national security anymore. Furthermore, computing centers could introduce transparency measures regarding the programs used. This could demonstrate, for example, that no nuclear weapon explosion simulation is carried out. The issue of conversion of research should be part of future research to develop adequate voluntary measures beyond the examples listed here.

Detecting undeclared facilities

The fourth verification objective, detecting undeclared facilities, is the most difficult to achieve. As pointed out above, this objective can apply to both nuclear weapons states and non-nuclear weapon states alike. It could be discussed whether those states that had nuclear weapons in the past should receive more attention, because the knowledge of weapon production lives on even after facilities are dismantled. For non-nuclear weapon states, the IAEA's Additional Protocol (INFCIRC/540) provides tools to assure the absence of undeclared fissile material production. The protocol gives the Agency the right to access any facility in a country for short-notice on-site inspections should it have indications of undeclared fissile material production. Additional research will be needed to determine how these approaches could be transformed to make them applicable to nuclear weapon states, and to expand the scope from fissile material production to component manufacturing and nuclear weapon assembly.

Two technologies that have been discussed for the detection of clandestine fissile material production might warrant further exploration also for facilities of the nuclear enterprise. First, satellite imagery combined with change detection. Automatic tools exist to scan satellite images for changes.[61] For undeclared activities, change detection alone is not sufficient – many buildings change shape in a country at any given time. Advances in machine learning can help to identify relevant facilities. Already in 2010, researchers reported the ability to identify nuclear power plants,[62] news reports claim that government agencies can identify clandestine missiles.[63] If such progress can also allow for the automatic detection of the various facilities part of the nuclear enterprise is an open question that could be addressed in future research activities.

Second, environmental sampling. The chapter *Nuclear Monitoring and Verification Without Onsite Access* discusses the applicability of environmental sampling to detect fissile material production facilities. Future research could explore whether certain undeclared facilities in the nuclear enterprise could be detected based on trace emissions of the materials processed. Some facilities process materials including plutonium, uranium or tritium, as well as conventional high explosives. The quantities of handled materials – and thus potential emissions – are relatively small compared to fissile material production. Therefore, even very intensive wide area environmental sampling approaches will not provide absolute confidence that no facility exists. Rather, methods should be explored that could, combined with other inspections, increase the risk of detection of individual sites and thus help deter states from engaging in larger clandestine activities.

Again, international experience on detecting clandestine facilities related to nuclear weapon production is relatively limited. The approaches listed above are hardly ready proposals, rather they are an agenda for future research that would explore whether or under what circumstances they are applicable to this verification objective.

Conclusion

This article identified four key verification objectives for the elimination or conversion of a country's nuclear enterprise. The nuclear enterprise is understood here as all production and research installations beyond fissile material production, i.e., research and development, component manufacturing, and weapon assembly. The verification objectives would ensure that facilities terminate operation, are eliminated, or converted to other purposes distinct from nuclear weapon production. Also, undeclared, clandestine facilities need to be identified. The last objective applies both to former nuclear weapon states and non-nuclear weapon states.

Facilities and objects to be monitored have been listed based on two methods: First, along the production requirements for the commonly known components of nuclear weapons. Second, based on past experiences with detecting clandestine nuclear weapon programs in non-nuclear weapon states. Future disarmament agreements will need to turn the compilation into "item lists" of facilities, material, equipment and processes that should be prohibited or only used under control. Such a list can be similar, for example, to the list in Annex 3 of the "Plan for Future Ongoing Monitoring and Verification" for the IAEA's inspection activities in Iraq. However, it will be necessary to discuss the extent of the list to balance the number of civilian activities with available inspection capacities – in particular when disarmament in multiples states with full-blown nuclear enterprises are to be monitored.

The previous section identified potential verification technologies for the different objectives. Several technologies have already been developed, often with regard to fissile material controls or other existing treaty regimes. These include perimeter control mechanisms, containment, and surveillance technology as well as remote monitoring for observation of larger structures. These technologies have a high readiness level but would need to be adapted for the special facilities in a nuclear enterprise.

For the objective to certify the conversion of facilities, the converted status of facilities needs to be defined first. As the definition depends more on political requirements than on technical aspects, it will likely be negotiated as part of future disarmament agreements. Verification technologies for the fourth verification objective, the ability to find undeclared facilities, need significant additional research. In the future, researchers should explore whether procedures from the IAEA's Additional Protocol could be adapted to the task: Could satellite imagery analysis be used to find the different types of potential facilities; and under which conditions could wide area environmental sampling contribute to the objective?

Future research should also analyze combinations of technologies to improve efficiency and effectiveness. As multiple nuclear weapon states already terminated weapon production in some facilities formerly part of their nuclear enterprise, tests of verification technologies and approaches could start soon with a low level of intrusiveness. This would provide a test-bed for approaches and prepare scientists, inspectors as well as policy makers for the challenges of more intrusive measures once respective agreements have been negotiated.

Endnotes

1 *Phase III Programme of Work*, International Partnership for Nuclear Disarmament Verification (IPNDV), June 2020. Available: *https://www.ipndv.org/wp-content/uploads/2020/06/IPNDV_Phase_III_Programme_of_Work.pdf*.

2 T. Nakane, *Main Elements to Be Considered for Effective Verification of Nuclear Disarmament*, Working Paper, GE-NDV/2018/10, Group of Governmental Experts to Consider the Role of Verification in Advancing Nuclear Disarmament, 2019. Available: *https://undocs.org/en/GE-NDV/2018/10*.

3 M. Biontino, *Considerations on the Role of Verification in Advancing Nuclear Disarmament: Background Paper*, Working Paper, GE-NDV/2018/4, Group of Governmental Experts to Consider the Role of Verification in Advancing Nuclear Disarmament, 2019. Available: *https://undocs.org/en/GE-NDV/2018/4*.

4 *Securing Our Survival – the Case for a Nuclear Weapons Convention*, International Physicians for the Prevention of Nuclear War, International Association of Lawyers Against Nuclear Arms, and International Network of Engineers and Scientists Against Proliferation, 2007. Available: .
The draft nuclear weapons convention text was also submitted by Costa Rica and Malaysia to the UN Secretary General (*Letter Dated 17 December 2007 from the Permanent Representatives of Costa Rica and Malaysia to the United Nations Addressed to the Secretary-General*, 2008. Available: *https://undocs.org/pdf?symbol=en/A/62/650*).

5 *Treaty on the Prohibition of Nuclear Weapons*, United Nations Office for Disarmament Affairs. Available: *https://www.un.org/disarmament/wmd/nuclear/tpnw/*.

6 Facilities where states manufacture nuclear weapons can be used to dismantle them, too. This is currently done in most nuclear weapon states, e.g. disassembling weapons for maintenance purposes or to dismantle surplus weapons. An alternative would be to use dedicated dismantlement facilities, which will simplify verification activities.

7 C. Comley, et al., *Confidence, Security & Verification: The Challenge of Global Nuclear Weapons Arms Control*, AWE/TR/2000/001, Atomic Weapons Establishment, 2000. Available: *http://fissilematerials.org/library/awe00.pdf*.

8 O. Bukharin and J. Doyle, "Verification of the Shutdown or Converted Status of Excess Warhead Production Capacity: Technology Options and Policy Issues," *Science & Global Security,* 10 (2), 2002, pp. 103–124.

9 *Phase III Programme of Work*, International Partnership for Nuclear Disarmament Verification (IPNDV).

10 T. Dalton, et al., *Toward a Nuclear Firewall: Bridging the NPT's Three Pillars*, Carnegie Endowment for International Peace, 2017. Available: *http://carnegieendowment.org/2017/03/20/toward-nuclear-firewall-bridging-npt-s-three-pillars-pub-68300*.

11 T. Patton, "An International Monitoring System for Verification to Support Both the Treaty on the Prohibition of Nuclear Weapons and the Nonproliferation Treaty," *Global Change, Peace & Security,* 30 (2), 2018, pp. 187–207. Available: *https://doi.org/10.1080/14781158.2018.1467392*.

12 The Treaty on the Prohibition of Nuclear Weapons requires thorough verification. However, detailed plans are only to be negotiated once nuclear weapon states decide to join.

13 For example: A.F. Woolf and J.D. Werner, *The U.S. Nuclear Weapons Complex: Overview of Department of Energy Sites*, CRS Report R45306, Congressional Research Service, 2020.

14 J. Medalia et al., *Nuclear Weapons R&D Organizations in Nine Nations*, CRS Report R40439 Congressional Research Service, 2013.

15 *The Defence Nuclear Enterprise a Landscape Review*, United Kingdom National Audit Office, 2018. Available: *https://www.nao.org.uk/report/the-defence-nuclear-enterprise-a-landscape-review/*.

16 T. B. Cochran, W. M. Arkin, R. S. Norris, and J. Sands, *Nuclear Weapons Databook. Volume IV – Soviet Nuclear Weapons*, Ballinger, Cambridge, Mass., 1989.

17 R. S. Norris, A. S. Burrows and R. W. Fieldhouse*, Nuclear Weapons Databook. Volume V – British, French, and Chinese Nuclear Weapons,* United States, 1994.

18 *Restricted Data Declassification Decisions 1946 to the Present (RDD 8)*, United States Department of Energy, 2002.

19 J. W. Toevs and C. A. Beard, *Gallium in Weapons-Grade Plutonium and MOX Fuel Fabrication*, LA-UR-96-4764, Los Alamos National Laboratory, 1996. Available: *http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-96-4764*.

20 S. K. Weiner, “Reconsidering U.S. Plutonium Pit Production Plans,” *Arms Control Today*, June 2020. Available: *https://www.armscontrol.org/act/2020-06/features/reconsidering-us-plutonium-pit-production-plans*.

21 O. Bukharin and J. Doyle, 2002, op. cit.

22 O. Bukharin and J. Doyle, 2002, op. cit.

23 “Pantex Lays Nukes to Rest,” *Bulletin of the Atomic Scientists* 48 (8), Oct 1992, pp. 48–49. Available: *https://doi.org/10.1080/00963402.1992.11460117*.

24 W. Spivey, *Devils in the Details*, Los Alamos National Laboratory, 2019. Available: *https://www.lanl.gov/discover/publications/national-security-science/2019-fall/devils-in-the-details.php* (accessed September 25, 2020).

25 B. C. Reed, “Rousing the Dragon: Polonium Production for Neutron Generators in the Manhattan Project,” *American Journal of Physics*, 87 (5), May, 2019, pp. 377–83. Available: *https://doi.org/10.1119/1.5094138*.

26 T. J. Gardner, C. L. Renschler, and M. M. Archuleta, *Neutron Generator Enterprise at Sandia National Laboratories (U)*, Sandia National Laboratories. Available: *https://www.osti.gov/biblio/1339208*.

27 *Pinellas Plant Facts*, United States Department of Energy, Pinellas Area Office and GE Neutron Devices, 1990, p. 49. Available: *https://core.ac.uk/download/pdf/187437133.pdf*.

28 *The Explosive Technologies Group*, Sandia National Laboratories, 2018. Available: *https://www.sandia.gov/news/publications/fact_sheets/_assets/documents/Expl_Tech_Gr_2018.pdf*.

29 M. B. Kalinowski and L. C. Colschen, “International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament,” *Science & Global Security*, 5 (2), August, 1995, pp. 131–203. Available: *https://doi.org/10.1080/08929889508426422*.

30 J. Medalia et al., 2013, op. cit.

31 Israel never publicly declared to have tested nuclear weapons. However, it is widely believed that an event detected in 1979 by United States satellites (“Vela Incident”) was a test of a nuclear weapon, and it is commonly attributed to Israel. (W. Burr et al., “Blast From the Past.” *Foreign Policy*, 2019. Available: *https://foreignpolicy.com/2019/09/22/blast-from-the-past-vela-satellite-israel-nuclear-double-flash-1979-ptbt-south-atlantic-south-africa/*).

32 *On-Site-Inspections*, Comprehensive Nuclear-Test Ban Treaty Organisation. Available : *https://www.ctbto.org/verification-regime/on-site-inspection/the-final-verification-measure/*.

33 *Top500 List*, November 2020. Available: *https://top500.org/lists/top500/list/2020/11/*.

34 A. von Baeckmann, G. Dillon and D. Perricos, “Nuclear Verification in South Africa,” *IAEA Bulletin*, 1995. Available: *https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull37-1/37105394248.pdf*.

35 *Letter Dated 6 October 1997 from the Director General of the International Atomic Energy Agency to the Secretary-General*, UN Security Council, S/1997/779, 1997.

36 Annex 3 to the IAEA Ongoing Monitoring and Verification Plan for Iraq. A version of this document is published as UN Security Council Document S/2001/561. Available: https://undocs.org/en/S/2001/561.

37 *Implementation of the NPT Safeguards Agreement of the Socialist People’s Libyan Arab Jamahiriya*, Report by the Director General, GOV/2004/33, International Atomic Energy Agency, 2004; *Implementation of the NPT Safeguards Agreement of the Socialist People’s Libyan Arab Jamahiriya*, Report by the Director General, GOV/2004/12, International Atomic Energy Agency, 2004.

38 *Pinellas Plant – United States Nuclear Forces*, GlobalSecurity.org. Available: *https://www.globalsecurity.org/wmd/facility/pinellas.htm* (accessed September 26, 2020).

39 *Young-Rainey Science Technology and Research (STAR) Center*. Available: *http://www.young-raineystarcenter.org/*.

40 S. Fetter, “Nuclear Archaeology: Verifying Declarations of Fissile-material Production,” *Science & Global Security,* 3 (3–4), March 1993, pp. 237–59. Available: *https://doi.org/10.1080/08929889308426386*.

41 J.P. Harahan, *On-Site Inspections Under the INF Treaty – a History of the On-Site Inspection Agency and Treaty Implementation, 1988-1991*, The On-Site Inspection Agency, United States Department of Defense, Washington, D.C., 1993.

42 J. Russell, "On-Site Inspections Under the INF Treaty: A Post-Mortem," *VERTIC Briefing Paper*, 1 (2), 2001.

43 C. Hobbs, P. McBurney and D. Oliver, "Data Science in Support of Radiation Detection for Border Monitoring: An Exploratory Study," *Science & Global Security*, 28 (1), January, 2020, pp 28–47. Available: *https://doi.org/10.1080/08929882.2020.1716461*.

44 B. D. Geelhood, J. H. Ely, R. R. Hansen, R. T. Kouzes, J. E. Schweppe, and R. A. Warner, "Overview of Portal Monitoring at Border Crossings," *2003 IEEE Nuclear Science Symposium*, 2003. Available: https://doi.org/10.1109/NSSMIC.2003.1352095; E. Guardincerri et al., "Detecting Special Nuclear Material Using Muon-Induced Neutron Emission," *Nuclear Instruments and Methods in Physics Research A*,789, 2015, pp. 109-113. Available: *https://doi.org/10.1016/j.nima.2015.03.070*.

45 T. Patton, 2018, op. cit.

46 A. Graef and M. Kütt, *Visualizing the Open Skies Treaty*, 2020. Available: *http://www.openskies.flights*.

47 *Containment and Surveillance An Overview*, SAND2013-8685C, International Safeguards and Technical Systems Department, Sandia National Laboratories, 2013. Available: *https://www.osti.gov/servlets/purl/1114595*.

48 *Safeguards Techniques and Equipment*, International Nuclear Verification Series, International Atomic Energy Agency, 2011.

49 E. R. Gerdes, R. G. Johnston, and J. E. Doyle, "A Proposed Approach for Monitoring Nuclear Warhead Dismantlement," *Science & Global Security*, 9 (2), January, 2001, pp. 113–41. Available: *https://doi.org/10.1080/08929880108426491*.

50 T. R. Lockner et al., *Progress towards Complimentary Cooperative Monitoring Facilities at the Savannah River Site, USA and VNIIEF,RF*, SAND2000-1590C, Sandia National Laboratories, 2000. Available: *https://www.osti.gov/biblio/760794-progress-towards-complimentary-cooperative-monitoring-facilities-savannah-river-site-usa-vniief-rf*.

51 C. Comley et al., 2000, op. cit.; O. Bukharin and J. Doyle, 2002, op. cit.

52 B. Haas and J. Borger, "North Korea 'destroys' Nuclear Test Site as World's Media Watches," *The Guardian*, May 24, 2018. Available: *https://www.theguardian.com/world/2018/may/24/north-korea-destroys-nuclear-test-site-as-worlds-media-watches*.

53 *Letter Dated 6 October 1997 from the Director General of the International Atomic Energy Agency to the Secretary-General*, S/1997/779, UN Security Council, 1997.

54 A comprehensive discussion of the issue of knowledge can be found in D. MacKenzie and G. Spinardi. "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons." *American Journal of Sociology,* 101 (1), 1995, pp. 44–99.

55 *K-25 History Center*, United States National Park Service. Available: *https://www.nps.gov/places/k-25-history-center.htm*.

56 A list of equipment and materials destroyed can be found in Attachment 3.1 of *Letter Dated 6 October 1997 from the Director General of the International Atomic Energy Agency to the Secretary-General*, 1997, op. cit.

57 A. von Baeckmann, G. Dillon, and D. Perricos , 1995, op. cit.

58 For an early discussion of conversion possibilities: J. Reppy, ed., *Conversion of Military R&D*, Basingstoke, Hampshire: Macmillan, 1998.

59 For example, in the United States: *Virtual Nuclear Weapons Design and the Blur of Reality*, The MIT Press Reader, February, 2020. Available: *https://thereader.mitpress.mit.edu/virtual-nuclear-weapons-design-and-the-blur-of-reality/*.

60 *Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities*, Max-Planck-Gesellschaft, 2003. Available: *https://openaccess.mpg.de/Berlin-Declaration*.

61 S. Nussbaum, I. Niemeyer, and M. J. Canty, "SEATH–a New Tool for Automated Feature Extraction in the Context of Object-Based Image Analysis," *Proc 1st International Conference on Object-Based Image Analysis (OBIA 2006)*, ISPRS, 36, 2006.

62 R. R. Vatsavai, A. Cheriyadat, and S. Gleason, "Supervised Semantic Classification for Nuclear Proliferation Monitoring," *2010 IEEE 39th Applied Imagery Pattern Recognition Workshop (AIPR)*, 2010. Available: *https://doi.org/10.1109/AIPR.2010.5759712*.

63 P. Stewart, *INSIGHT-Deep in the Pentagon, a secret AI program to find hidden nuclear missiles,* Reuters, June 5, 2018. Available: *https://fr.reuters.com/article/usa-pentagon-missiles-ai-idUSL2N1ST1GG*.

6. Conclusion: Building up Transparency and Verification

MALTE GÖTTSCHE AND ALEXANDER GLASER

There is a widely-shared expectation that a future round – and perhaps even the next round – of nuclear arms-control agreements could set limits on the total numbers of warheads in the nuclear arsenals. Such agreements would not only include deployed strategic weapons but also warheads in storage and, perhaps, warheads slated for dismantlement. Verified limits on warhead stockpiles would represent an important new milestone for nuclear arms control. An exclusive focus on warheads and their delivery systems will, however, be insufficient: Given that most weapon states possess stocks of weapon-usable fissile materials that are sufficient for hundreds or thousands of additional weapons, a sustainable path towards disarmament will at some point also require constraints on inventories and the production of fissile materials, as well as include the disposition of these materials.

Verification will need to become even more comprehensive when moving closer towards, and later-on seeking to maintain, zero weapons. This may require the elimination or conversion of nuclear weapon production and research capabilities. Indeed, verification of nuclear disarmament in South Africa – the only precedent so far – focused on warheads, fissile materials, and the weapon program.

All these different aspects suggest that disarmament verification requires a suite of approaches and measures. Moreover, debates on nuclear disarmament verification need to be inclusive: it is important not to narrow down the available options too quickly. There is not *the* one way or *the* one central aspect of how to verify disarmament, and different options could be explored and developed simultaneously. The debate should also be inclusive with regard to those who participate in it. It is important to seek input from a broad range of stakeholders – ideally, also including all nuclear weapon states – about their ideas for how to approach the challenge.

With this report, we attempted to provide a broad overview of the technical challenges associated with disarmament verification. Several conclusions can be drawn.

1. A future international exercise should focus on verifying the absence of nuclear weapons, the most urgent and immediately useful verification task. This could be an opportunity to involve Russia, China, and possibly other weapon states.

Several international initiatives, most notably the International Partnership for Nuclear Disarmament Verification (IPNDV), have focused their work on the issue of verified warhead dismantlement – including the challenge of making sensitive measurements to confirm the authenticity of warheads. This engagement has been important as it has demonstrated that multilateral cooperation in this area is possible, and that non-nuclear weapon states can actively participate even on some of the most sensitive aspects.

Warhead dismantlements may, however, not be verified anytime soon. In fact, dismantlements have been ongoing on a routine basis in all weapon states for years and decades, and about 90% of all warheads that ever existed have already been taken apart – often, of course, to recover the fissile material for use in new weapons. While unverified dismantlements may pose certain challenges, it is reasonable to consider verification approaches that do not focus on the physical dismantlement process – at least not from the outset.

More pressing are approaches that could instead work with measurements to confirm that items beyond those declared to be treaty accountable are in fact *not* warheads ("absence verification"). Established under New START for deployed weapons, and as argued in this report, this approach could also be adequate for verifying limits on warhead numbers, i.e., by accepting all declared items as treaty accountable while ensuring that other objects on a site are in fact not treaty accountable.

A focus on such approaches may help convince Russia, China, and several other weapon states that have not engaged much on disarmament verification internationally to join and support future efforts. In IPNDV, they observe but do not actively participate. There is a risk that disarmament verification technologies and approaches might never be used or implemented, if some weapon states did not participate in their development. It is therefore crucial to reach out and engage these states at an early date, but they will only do so if they see value in such efforts. The benefit of discussing absence verification in this respect is three-fold:

First, it is well-suited to monitor possible elements of a New START follow-on agreement between the United States and Russia, which is an incentive for both states to engage. Specifically – beyond upper ceilings of deployed warheads – various limitations on tactical and non-deployed warheads could be verified this way (for example, overall or locational restrictions of non-deployed warheads or provisions requiring the absence of deployed tactical weapons.)[1] Doubts of some Russian analysts "about the ability of abstract verification 'recipes' to facilitate progress towards nuclear disarmament"[2] may not apply to these proposals, which take into consideration concrete strategic factors and objectives.

Second, China has stated that "relevant research should address the simplest issues first and move forward in a sequential manner."[3] As opposed to verified warhead dismantlement, absence verification can be considered relatively straightforward, as no sensitive items are involved in the process. In fact, the relevant technologies and approaches exist, and they have been accepted and used by Russia and the United States for years. As part of other bilateral or multilateral arms-control agreements, they could be implemented elsewhere without much if any additional research and development.

Third, as discussed in the report, absence verification is deliberately not aimed at revealing details about arsenals and operations. This can be considered advantageous, as some weapon states may actually prefer some level of ambiguity at an early stage of the disarmament process. It may enable states without much prior experience in nuclear arms control to come on board.

An immediate path forward would be to hold an international exercise fully centered on this challenge. A useful starting point was the LETTERPRESS exercise of the Quadrilateral Nuclear Verification Partnership (QUAD). It included some absence verification measurements though limited to items that were "declared to contain plutonium," i.e., the scenario did not consider the need to inspect items that may contain uranium only and require other types of instruments or procedures.[4] It is commendable that this and other exercises have included participants from some non-nuclear weapon states, but it would be equally significant at this point to encourage broader participation including also from other weapon states.

2. In addition to formal verification, transparency measures play a key role to ensure that the confidence required for disarmament is obtainable. They should be introduced gradually using smart approaches – starting today.

As long as vast weapons arsenals exist, some uncertainty and ambiguity in military capabilities and stockpiles may be considered acceptable by military planners and arms-control negotiators. As reductions proceed, however, this report highlights the importance of gradually reducing these ambiguities; at the same time, verification measures would become more comprehensive and rigorous. Ultimately, for nuclear disarmament to succeed, there must be high confidence in the absence of inventories of undeclared nuclear weapons or fissile materials as well as undeclared nuclear facilities and related activities. This report finds that – in addition to formal verification measures – additional transparency measures play a key role in reducing uncertainty and in building the confidence required for disarmament.

First, it is difficult to agree on specific verification measures, including for example those involving onsite inspections, unless sufficient confidence has been built upfront. If, for example, states have previously – and ideally in a reciprocal manner – declared information on warhead or fissile material stockpiles, the step to later implement more formal verification measures to confirm those numbers may be smaller than without such prior insight.

Second, transparency measures accelerate the confidence-building process. Even though a declaration by itself may initially not be verifiable, such transparency measures are an important cornerstone to support the monitoring of future agreements: Any data obtained during formal verification activities can be checked for consistency with information obtained from earlier transparency initiatives.

Finally, transparency measures might actually be *required* to obtain confidence in complete disarmament. This report finds that there are currently no technology-based verification approaches that could ensure with high confidence the early detection of undeclared warheads, stocks of fissile material, or related sites. These capabilities may in fact never exist, but some important gaps can be closed by a long record of transparency and good-faith cooperation. In this case – and perhaps only then – can the international community have built a sufficiently deep understanding of the nuclear enterprises maintained by the weapon states to be confident that disarmament has been completed.

That said, proposals to increase transparency have not received much traction. In fact, in March 2021, the United Kingdom reversed transparency policies established in the 1990s, declaring that it will from now on pursue "deliberate ambiguity and no longer give public figures for our operational stockpile, deployed warhead or deployed missile numbers;"[5] similarly, the United States has not pursued its transparency efforts launched in the 1990s with the same level of effort and creativity. More generally, states may be afraid to prematurely hand over militarily significant information before an agreement is reached.

To address this concern, here, we propose what one might call "smart transparency" as a path to engage weapon states in transparency efforts at an early stage. If implemented correctly, it does not imply the unfettered release of swaths of information; what matters instead is to make a genuine effort to document historic activities and inventories, even if for internal use at first, but to demonstrate publicly that this work has been done. These efforts can then lay the basis for unilateral, bilateral, or multilateral steps toward public declarations and other confidence-building measures as arsenals are pared down.

In particular, this report proposes secure declarations that commit states to their content, but protect sensitive information until states are ready to share it. Even though information is technically declared upfront, this is done in a secure format such that the cleartext cannot be read by others, and states can choose to reveal it only gradually. As opposed to voluntary unilateral initiatives, such a process could be coordinated among weapon states at an early date. Any initial information release can be narrow. With regard to fissile materials, for instance, the report suggests that – as a first step – information on former or current military fissile-material production facilities could be released. States could first declare locations, size, and technology of their facilities. Information on inventories could be limited to HEU and plutonium stocks as one single number each.

3. The discussion of nuclear disarmament verification must be significantly broadened beyond warhead dismantlement and, in particular, place greater emphasis on monitoring fissile materials. In general, verification approaches that support the irreversibility of disarmament, but are at the same time as non-intrusive as possible, should be prioritized.

The discussion on verified warhead dismantlement and warhead confirmation measurements has resulted in a deeper understanding of the related challenges, but it has taken up most of the space in the recent verification debate. While its contributions have been acknowledged in this report, for two reasons, it is time to broaden the discussion on how to verify nuclear disarmament.

First, warhead confirmation measurements are difficult to conduct as inspectors require direct access to nuclear weapons, and information considered sensitive or classified is typically acquired in the process. It has proven difficult to ensure that this information is protected from the inspectors' view even if the equipment malfunctions or is operated incorrectly (certification) and that the system measures, processes, and presents the results based on the measurements in an accurate manner (authentication).

Second, and more significantly, verified dismantlement is only one particular aspect of a much larger verification framework required for nuclear disarmament.[6] Importantly, the warhead dismantlement process itself is rather reversible: the components can be re-constituted. For disarmament to be irreversible, the disposition or future use of the recovered fissile materials must also be verified in the medium term, considering that existing stocks and those resulting from dismantlement can be used to produce new warheads. Actually, approaches that shift the focus from warhead verification to fissile material verification have already been envisaged.[7] The most irreversible long-term approach would be to verify the elimination of the nuclear weapon enterprise as a whole.

Therefore, beyond warhead dismantlement, the focus ought to shift to or re-emphasize such other important elements of the verification toolbox; they should be considered and examined in similar detail, initially focusing on those required in the medium term. Generally speaking, the key goal is to develop robust measures best-suited to build confidence in disarmament. Where possible, measures designed to manage or minimize intrusiveness are to be preferred, in order to increase their acceptance.

Less intrusive alternatives for monitoring warhead limitations and reductions have been suggested in the report. For instance, if onsite inspections are considered too difficult for some sensitive sites – including for absence verification – at least in the early phases of an agreement, "secure virtual inspections" could be a possible alternative, as they do not require physical access.

Compared to warhead monitoring, approaches to verify declared fissile-material inventories and production in weapon states are underdeveloped and require much more attention. Given that most weapon states have fissile-material stockpiles that far exceed even their current requirements, verifying existing inventories can be considered just as important as a verified end of fissile-material production for weapons purposes.

While inventories could be verified with material accountancy measures, doing so with nuclear archaeology would be less intrusive, as it does not require direct access to the materials. Nuclear archaeology includes methods and tools to reconstruct fissile-material production histories by means of examining documentation and conducting forensic measurements in shut-down facilities. Its importance is underlined by the IAEA's verification approach in South Africa, which largely focused on evaluating fissile-material production records.[8] A robust nuclear archaeology capability also applicable to weapon programs larger than the South African one does not exist today, but it can and must be developed.

To verify fissile-material production, the report highlights opportunities to replace or reduce the role of onsite inspections, which are often considered particularly intrusive, especially in military nuclear facilities. To verify a production stop, satellite imagery and standoff detection measures are proposed. The latter requires further study, as it is not used in safeguards. To monitor ongoing operations, in addition to the previous approaches, the report examines perimeter monitoring as a complement or alternative, another method the IAEA does not currently use. The challenges to timely detect undeclared production facilities remain significant, but they also exist in nuclear safeguards in non-nuclear weapon states.

4. Gaps in scientific methods and technology for disarmament verification can only be closed with a sustained commitment to research and development. International collaboration can be facilitated by a Group of Scientific and Technical Experts and joint experiments.

While the technologies required for verifying the next reduction steps are already available, this report and others – including some of those published by the IPNDV[9] – have identified numerous gaps. Based on the current state-of-the-art, some aspects of nuclear disarmament would be difficult to verify today.

The most notable research gaps identified in this report are related to nuclear archaeology, viable approaches for perimeter monitoring or standoff detection, capabilities to detect undeclared fissile-material production, and methods to verify the elimination of nuclear weapon production and research capabilities.

Those hard scientific gaps can neither be closed by international discussions, such as those facilitated by the IPNDV, nor by verification exercises alone – though both are suited to better understand challenges, test proposed solutions, and to some extent identify technology gaps. Instead, closing these gaps can only be achieved by years' worth of sustained scientific and technical research and development at laboratories and academic institutions.

If a global capacity on disarmament verification technology is sought, at least three elements can be proposed. First and foremost, it is essential for a larger number of states to commit to a sustained scientific research effort. Second, a Group of Scientific and Technical Experts can facilitate and coordinate international research collaboration. Lastly, beyond exercises to practice verification protocols, international experiments can be conducted to support the joint development of technologies and scientific methods. In particular, closed-down fuel cycle facilities in both nuclear weapon and non-nuclear weapon states could be used as test beds to further develop nuclear archaeology methods.

Given the complex research tasks, only a strong and continuous engagement can ensure that methods and technologies will be available when they are needed. Throughout the disarmament process, such an effort must go hand-in-hand with a careful expansion of transparency measures and the phasing in of verification activities. Only if this is planned with foresight, will there be sufficient time to address all issues necessary to enable deep cuts and move toward a world without nuclear weapons.

Endnotes

1 A. Diakov, G. Neuneck and L. Rusten, *New START: Extension under what Circumstances?* Deep Cuts Issue Brief 14, October 2020; and P. Podvig and J. Serrat, *Lock Them Up: Zero-deployed Non-strategic Nuclear Weapons in Europe*, UNIDIR, 2017.

2 A. Malov, "Anything useful on the 'menu'? Approaches to verification of multilateral nuclear disarmament," in V. Orlov and A. Zulkharneev (eds.), *Verification of nuclear arms control and nuclear disarmament: experience, prospects, and new ideas*, PIR Center Trialogue, 2020.

3 *Nuclear disarmament verification: Report of the Secretary-General*, United Nations, A/75/126, 2020, p.7.

4 *LETTERPRESS: Post-Simulation Report*, Quad Nuclear Verification Partnership. Available: *https://quad-nvp.info/wp-content/uploads/2020/11/LP-Post-Simulation-Report_P2P.pdf*.

5 *Global Britain in a competitive age: The Integrated Review of Security, Defence, Development and Foreign Policy*, United Kingdom, March 2021.

6 *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, Committee on International Security and Arms Control, National Academies Press, 2005;
Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks, Nuclear Threat Initiative, 2014. Available: *https://www.nti.org/analysis/reports/innovating-verification-new-tools-new-actors-reduce-nuclear-risks/*.

7 P. Podvig and J. Rodgers, *Deferred Verification: Verifiable Declarations of Fissile-Material Stocks for Disarmament Purposes*, UNIDIR, 2017.

8 A. von Baeckmann, G. Dillon and D. Perricos, "Nuclear verification in South Africa," *IAEA Bulletin*, no. 1, 1995.

9 *Technology Gaps Identified*, IPNDV Working Group 6, April 2020. Available: *https://www.ipndv.org/wp-content/uploads/2020/04/IPNDV_WG6_Gap_analysis_FINAL.pdf*.

Authors

Mona Dreicer retired from Lawrence Livermore National Laboratory as the Deputy Director of the Center for Global Security Research. Previously, she served as Director of the Office of Nuclear Affairs at the U.S. State Department assessing verification and compliance with nuclear arms control treaties. She has worked on nonproliferation, threat reduction and other topics for governments, national laboratories, the IAEA, and a French nonprofit research organization. Dreicer holds a doctorate from l'Ecole des Mines de Paris, France.

Alexander Glaser is associate professor in the School of Public and International Affairs and in the Department of Mechanical and Aerospace Engineering at Princeton University. He co-directs Princeton's Program on Science and Global Security. In 2020, Glaser has been elected a Fellow of the American Physical Society (APS) for "major contributions to advancing the scientific and technical basis for nuclear arms control, nonproliferation, and disarmament verification." Glaser holds a PhD in physics from Darmstadt University, Germany.

Malte Göttsche is junior professor at RWTH Aachen University, where he leads the Nuclear Verification and Disarmament Group. Previously, he was postdoc in Princeton University's Program on Science and Global Security. Göttsche develops concepts and scientific techniques for nuclear disarmament verification. He is a Young Academy Fellow of the North Rhine-Westphalian Academy of Sciences, and a Freigeist Fellow of the Volkswagen Foundation. Göttsche holds a doctorate in physics from the University of Hamburg.

Moritz Kütt is a Senior Researcher at the Institute for Peace Research and Security Policy at the University of Hamburg. Previously, he was postdoc in Princeton University's Program on Science and Global Security. In his research, he develops new technical and political approaches for nuclear disarmament verification. Kütt holds a doctorate in physics from the Technische Universität Darmstadt.

Irmgard (Irmie) Niemeyer is head of the Nuclear Safety and Safeguards Division at Forschungszentrum Jülich. Her responsibilities include the scientific coordination of programs in international safeguards, nonproliferation and disarmament. Niemeyer is member of the Standing Advisory Group on Safeguards Implementation, the International Partnership for Nuclear Disarmament Verification, and the UN Governmental Group of Experts on Nuclear Disarmament Verification (2021/22). She holds a doctorate in geography from the University of Bonn.

Sébastien Philippe is an Associate Research Scholar and Lecturer at Princeton University and a member of the Program on Science and Global Security where he works on nuclear weapons and emerging technologies issues. Philippe is also an associate faculty at Sciences-Po, associate editor of the journal Science and Global Security, and a member of the International Panel on Fissile Materials. He holds a PhD in mechanical and aerospace engineering from Princeton.

Sharon Squassoni is a research professor at the Institute for International Science and Technology Policy at George Washington University. Her work has focused on reducing risks from nuclear energy and weapons for three decades. Squassoni has held senior positions at the U.S. State Department, the Arms Control and Disarmament Agency and the Congressional Research Service. She is on the Science and Security Board of the Bulletin of Atomic Scientists, the PIR Center and the Center for Arms Control and Nonproliferation.

Imprint

Published by
Federal Foreign Office
Division Nuclear Disarmament, Arms Control, Non-Proliferation (OR09)
Werderscher Markt 1
10117 Berlin
Internet: *www.diplo.de*

The publication can be downloaded at
www.diplo.de/publications

Editors
Malte Göttsche (RWTH Aachen University)
Alexander Glaser (Princeton University)

Assistant to the Editors
Jakob Brochhaus (RWTH Aachen University)

Layout
kionodesign
www.kiono.de

Printed by
Druck- und Verlagshaus Zarbock GmbH & Co. KG
Sontraer Str. 6
60386 Frankfurt a.M.

Title
A Sandia researcher demonstrates new radiation detection equipment for New START treaty monitoring.
© R. Montoya for Sandia National Laboratories

As of April 2021