VERIFICATIONMATTERS

VERTIC RESEARCH REPORTS ● NUMBER 12 ● NOVEMBER 2015

# Exploring Multilateral Verification of Nuclear Disarmament: Scenarios, Modelling and Simulations

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## About VERTIC

The Verification Research, Training and Information Centre is an independent, not-for-profit non-governmental organization. Our mission is to support the development, implementation and effectiveness of international agreements and related regional and national initiatives. We focus on agreements and initiatives in the areas of arms control, disarmament and the environment, with particular attention to issues of monitoring, review and verification.

VERTIC conducts research and analysis and provides expert advice and information to governments and other stakeholders. We also provide support through capacity building, training, legislative assistance and cooperation.

We engage closely with governments, policy-makers and international organizations, as well as with the private sector and technical, academic and non-governmental communities worldwide.

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# About the report

There is growing demand for a more inclusive approach to exploring nuclear disarmament verification. At the 2010 Non-Proliferation Treaty Review Conference, states parties to the NPT have agreed on the importance of supporting cooperation 'aimed at increasing confidence, improving transparency and developing efficient verification capabilities related to nuclear disarmament.' This report aims to support such cooperation by describing a means of:

- developing and testing multilateral approaches to verifying a wide range of possible nuclear disarmament situations, and;
- building the capacity of stakeholders to engage with the development and implementation of such approaches in a cost-effective and structured manner.

The report provides a guide for developing simulation exercises to consider the technical, legal and political challenges involved in verifying nuclear disarmament. It explains how creating nuclear disarmament 'scenarios' and technical models of nuclear programmes can provide detailed and holistic environments in which to run these simulations. It also discusses questions that need to be addressed while exploring disarmament verification options to ensure that any proposed solutions are reliable, coherent, trusted and accessible.

This publication is aimed at officials and experts concerned with arms control and disarmament verification issues in general, and nuclear disarmament and multilateral verification approaches in particular. It seeks to be a useful resource for officials both from governments and international organisations, as well as for independent experts, and research and capacity-building organisations.

The introduction to the report discusses how verification of nuclear disarmament has been explored to date, and outlines the demand for a wider scope and a more multilateral approach. The report then lays out the aims and methods of verification arrangements in general, and establishes the importance of context in determining suitable verification systems. Next, it provides an outline of two key components of verification systems in the nuclear field, the role of equipment in verification, and the manner in which common understandings of verification systems can be developed. The report then proposes an approach to carrying out simulations that can develop and test multilateral approaches to nuclear disarmament verification. It discusses how these simulations can inform policy toward nuclear disarmament verification, explore the application of verification technologies, and build shared understandings of verification for an array of disarmament situations. It then explains how to develop hypothetical disarmament scenarios and state-wide nuclear fuel cycle models to support these simulations.

This report forms part of an ongoing project run by VERTIC to support multilateral verification of nuclear disarmament, and to examine the role that international organisations can play in a multilateral approach. The project involves exploring technical, policy and legal verification issues with assistance from a range of experts. It also aims to increase capacity across countries, but in particular in non-nuclear-weapon states, to engage in nuclear disarmament verification. It seeks to achieve these aims through running educational seminars, regional meetings, expert workshops, surveys, exercises and through producing a series of technical resources including guides and reference volumes, among other activities.

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# List of acronyms

| | |
|---|---|
| **AGR** | Advanced Gas-cooled Reactor |
| **AMS** | Attribute Measurement System |
| **AVNG** | Attribute Verification by Neutron and Gamma Ray Assay |
| **BWR** | Boiling Water Reactor |
| **CIVET** | Controlled Intrusiveness Verification Technology |
| **CTBT** | Comprehensive Test Ban Treaty |
| **CWC** | Chemical Weapons Convention |
| **DIV** | Design Information Verification |
| **DPRK** | Democratic People's Republic of Korea, also known as North Korea |
| **FEDT** | Fork Detector irradiated fuel measuring system |
| **FMCT** | Fissile Material Cut-off Treaty |
| **IAEA** | International Atomic Energy Agency |
| **LEU** | Low-Enriched Uranium, uranium enriched below 5 per cent Uranium-235 |
| **LWR** | Light Water Reactor |
| **MOX** | Mixed Oxide fuel |
| **NDA** | Non-Destructive Assay |
| **NNSA** | US National Nuclear Security Administration |
| **NNWS** | Non-Nuclear-Weapon States under the NPT |
| **NPT** | Non-Proliferation Treaty |
| **NWS** | Nuclear-Weapon States under the NPT |
| **PHWR** | Pressurised Heavy Water Reactor |
| **PMDA** | Plutonium Management and Disposition Agreement |

| | |
|---|---|
| **PUREX** | Plutonium-Uranium Extraction process |
| **PWR** | Pressurised Water Reactor |
| **SWU** | Separative Work Units |
| **TAI** | Treaty-Accountable Items |
| **TRADS** | Trusted Radiation Attribute Demonstration System |
| **TRIS** | Trusted Radiation Inspection System |
| **UKNI** | UK-Norway Initiative |

# 1. Introduction

Nuclear weapons were seen as a stabilising force—something that kept the peace—throughout much of the Cold War. After the Soviet Union dissolved in 1991, the utility of nuclear arms diminished. This was evidenced by a steep decline in the numbers of operational nuclear weapons. The scale of reductions has been striking. In 1991, weapons-possessing states together held about 50,000 weapons. Nine years later, their possessions had been slashed to half that number. In 2015, the total stood at about 10,000 weapons, or one-fifth of the levels at the end of the Cold War.

Over the last twenty years, the trend has been toward progressively lower numbers. Nuclear armaments are now at a level not seen since the mid 1950s. However, the last decade has seen the rate of change tailing off. Numbers are still expected to fall, but at a far more modest rate. In the United States, President Obama's administration placed nuclear arms reductions high on the political agenda but progress has been slow, largely due to the Russian Federation's stiff resistance to further mutual cuts combined with a reluctance to make further reductions unilaterally. Furthermore, most nuclear weapon states have engaged in modernisation programmes, and some—like the Russian Federation—are formulating more flexible policies on nuclear weapons use. In South Asia, and North and East Asia too, the primacy of nuclear weapons as a principal tool of deterrence appears undiminished.

The five nuclear-weapon states under the Nuclear Non-Proliferation Treaty (NPT) assert that they remain committed to their disarmament obligations under the treaty. Article VI of the NPT obliges *all* parties to pursue good-faith negotiations on effective measures relating to cessation of the nuclear arms race, to nuclear disarmament, and to general and complete disarmament. However, there is some uncertainty among states parties as to how these obligations should be fulfilled in practice.

The last consensus document to emerge from the NPT's review process included an 'Action Plan' on disarmament, non-proliferation and the peaceful uses of nuclear energy. Some progress has been made since this plan was adopted in 2010. The Permanent Five (P5) members of the UN Security Council have agreed on a glossary of nuclear terms, and have attempted to provide a standardized approach to reporting on relevant activities (though with piecemeal results so far). In many areas, however, implementation of the Action Plan has faltered.

Beyond this Action Plan, there is little consensus guiding states toward a world free of nuclear weapons. The most recent NPT Review Conference, in 2015, failed to produce a consensus document. The Conference on Disarmament—established to serve as the single multilateral disarmament negotiation forum of the international community—has failed to agree a sustainable programme of work since 1996. While the 'humanitarian consequences' initiative has rallied 121 countries to its pledge calling on states parties to the NPT to 'fill the legal gap for the prohibition and elimination of nuclear weapons', nuclear-armed states (and many non-nuclear-armed states) are treating this goal with suspicion.

During such periods of uncertainty, it is important to highlight and explore the shared values and principles that remain common to all stakeholders in nuclear disarmament. The prevailing thought—echoing distant conclusions in the 1946 Acheson-Lilienthal Report on the International Control of Atomic Energy—is that nuclear abolition ultimately needs to be done cooperatively.[1] The possession of nuclear weapons by a single state would, in a fully disarmed world, give that country an unparalleled military advantage.

Recognising this risk, states parties to the NPT have committed to apply the principles of 'irreversibility, verifiability, and transparency' in relation to the implementation of their treaty obligations—including those related to disarmament. They have also agreed on the importance of supporting cooperation 'aimed at increasing confidence, improving transparency and developing efficient verification capabilities related to nuclear disarmament'.[2]

## The role of verification in nuclear disarmament research initiatives

Designing verification capabilities requires tackling a host of complex and contentious technical, legal and political issues. Nevertheless, building an understanding about how an agreement might be verified plays a vital role in bringing about such an agreement.[3] From safeguarded non-proliferation under the NPT, verified limits on strategic arms between the US and Russia, to the Comprehensive Nuclear Test Ban Treaty (CTBT), and the Chemical Weapons Convention, there are many examples of arms control or disarmament agreements that have been constructed based on such an understanding.

Nuclear-armed states have long considered how reductions in nuclear weapons might be verified. As far back as the 1960s, the US Department of Defense and the US Arms Control and Disarmament Agency set up 'Project Cloud Gap' to test the feasibility of potential arms control and disarmament measures. The project culminated in 'Field Test 34', an experiment exploring how nuclear weapon dismantlement might be verified.[4] In the 1980s, the 'Black Sea Experiment' showed that the US and Soviet Union had identified the value of working collaboratively to understand how monitoring technologies could be used to identify a real nuclear warhead deployed on a Soviet Cruiser.[5]

By the middle of the 1990s, optimism for nuclear arms control in the US had grown to the extent that the US Department of Energy's Office of Arms Control and Nonproliferation commissioned technical studies into the monitoring of nuclear warhead dismantlement, anticipating the inclusion of such actions in a third START Treaty.[6] Since 2000, the US and UK have been cooperating to explore technologies and methodologies, such as 'managed access' and 'information barrier' concepts (see Section 3) that would enable the monitoring and verification of potential future nuclear disarmament initiatives.[7]

More recently, further collaborative work between countries has been undertaken. The UK and Norway—with contributions from VERTIC—established an initiative to assess approaches to non-nuclear-weapon-state involvement in verifying nuclear warhead dismantlement. The work initially focused on the need to control proliferative information and promote understanding between nuclear weapons states and non-nuclear-weapons states on verification constraints. In 2010, the UK-Norway Initiative also started to investigate a broader context for its warhead dismantlement work.

## A cooperative, multilateral approach to verification

In 2011, VERTIC began a long-term initiative to consider how a multilateral body or arrangement could carry out nuclear disarmament verification. VERTIC's project investigates the development of a tested, internationally accepted, comprehensive and effective verification system that could address the broad range of disarmament activities. The project involves exploring technical, policy and legal verification solutions through a structured programme of work involving stakeholders from several states and bodies. This will result in a series of guides, reference volumes and exercises.

The project focuses on bringing together a wide range of countries, and supporting on-going learning among them. It aims to increase the capacity of stakeholders from all types of country, but in particular non-nuclear-weapon states, to engage in disarmament verification. This aim is supported by holding educational seminars and other meetings, and planning regional activities, as well as through the resources mentioned above.

Work under the project to date suggests that there is a strong appetite among non-nuclear-weapon states to contribute to, and become a participant in, nuclear disarmament verification. A survey of states' views conducted through the project suggests that the International Atomic Energy Agency (IAEA) could play an important role in achieving this.[8] The project has responded by publishing an introduction to the issues associated with this role, which aims to build capacity and encourage debate among IAEA Member States on this issue.[9]

In 2015, the US Department of State and the Nuclear Threat Initiative launched a partnership with an international focus on nuclear disarmament verification. The International Partnership for Nuclear Disarmament

Verification (IPNDV) aims to assess approaches to monitoring and verification across the nuclear weaponisation lifecycle. Also in 2015, the UK-Norway Initiative announced it will seek to work with additional countries. A collection of research institutes in Germany have also joined to form a 'nuclear disarmament verification network' to discuss and explore technical approaches to verifying nuclear disarmament. A recent publication by the network recommends that their collaboration should be expanded to a European level, drawing on a wealth of safeguards and verification experience on the continent.[10]

There appears to be an opportunity, and appetite, to begin drawing together the threads of the initiatives and experiences to date, to fill the gaps, and develop a comprehensive approach to disarmament verification. Such an approach would consider how to verify the full range of disarmament activities, and how this could be achieved in a collaborative way. Indeed, there is much work remaining, both for more narrowly-focused and broader initiatives.

## Expanding the research agenda

Some states have made important progress—both unilaterally and bilaterally—in developing tools and equipment to help verify nuclear disarmament activities. Nevertheless, more work is required to turn these development efforts into fully deployable systems that provide monitoring information that a verifying party can authenticate, and a verified party can certify as safe and secure. A verification equipment strategy document developed by the US also suggests that more work is required to develop equipment that can be applied to new forms of nuclear materials and to new nuclear processes.[11]

The exploration of nuclear disarmament verification must also move beyond such technical research and development. More work is definitely required on the definitional side. For instance, the term 'nuclear weapon' is undefined in most international arms control agreements.[12] If, however, nuclear weapons were ever to be a unit of account, they would need to be more conclusively defined. Without definition it would be impossible to establish when a weapon would cease to be a unit of account. Work here is progressing within the P5 process, whose glossary defines it as a 'weapon assembly that is capable of producing an explosion and massive damage and destruction by the sudden release of energy instantaneously released from self-sustaining nuclear fission and/or fusion.'[13]

There are also many legal issues that require attention. In particular, integrating domestic regulations into nuclear disarmament agreements will present challenges that have not been adequately examined. This issue mostly concerns national official secrets regulations, as well as other areas of law such as health and safety regulations. The legal framework for nuclear disarmament would be very complicated if nuclear weapons were brought under a verification regime. The facilities where these devices are dismantled are often extremely sensitive for the host state, and may be deemed critically important for national defence.

Nuclear work in general is often subject to extensive regulation, and where explosives are involved, regulations relating to ordinance work would need to be taken into account too. For instance, safety regulations could place limits on how many inspectors are allowed to witness nuclear dismantlement at one time, and could also put in place limitations on items brought into the facility: ranging from admissible clothing to the types of electrical equipment that are deemed safe to operate in the vicinity of explosives.

Expanding nuclear disarmament beyond warhead dismantlement into other areas, such as nuclear material disposition, would also raise a number of new verification tasks that will require careful examination. For instance, once a nuclear explosive device is taken apart, the material lodged within the weapon will need to be disposed. What are the verification implications of this? What happens to fissile material production infrastructure in a state, and how can its peaceful use be verified? Moreover, how can other states be assured that a disarmed country has not concealed any weapons and that all weapons-usable material is accounted for and placed under international supervision?

## A comprehensive, modular approach

The range of issues identified here, and elsewhere in this report, points to a clear need for a dynamic research and development agenda on nuclear disarmament verification. Comprehensive studies are needed. Efforts that focus narrowly on a single disarmament activity have been, and will continue to be, useful for those wishing to understand discrete aspects of disarmament and its verification. But, relying on such approaches unavoidably risks ignoring the fundamental links between the particular disarmament activity under investigation and the remaining range of disarmament activities.

Comprehensive initiatives can be difficult to envisage and run. In particular, broad scope examinations are challenging to delineate and structure. It is moreover difficult to reach conclusions on verification solutions that are applicable to nuclear weapon states based on open-source information alone.

The study of nuclear disarmament verification to date has been exclusive: focussing on a very limited range of disarmament activities and involving only a few states. However, conclusions that may be relevant for one state may be irrelevant to another. Every case of nuclear disarmament is *sui generis*—unique to its circumstances. With this in mind, it may be easy to dismiss comprehensive studies as either incomplete or inapplicable to real-world situations. Adopting this point of view, however, overlooks the commonalities that can be found in every disarmament or arms reduction effort so far.

Disarmament verification studies can also suffer from being unvalidated. There are few cases of comprehensive nuclear disarmament and those that have occurred—South Africa's and Ukraine's experiences in particular—were tackled in an ad-hoc manner. Lacking a solid empirical basis to work on, disarmament verification studies can too easily rely on *a priori* assumptions or generalisations that have never been tested in practice.

This does not mean that it is impossible to study nuclear disarmament verification *a posteriori*, on the basis of observation and experiments. For instance, what if there is a way to both devise verification solutions and validate them using a surrogate nuclear weapon state? Is it even possible to create a believable surrogate?

One major challenge to studying disarmament verification is the multitude of various scenarios and alternative futures one would need to take into account at the outset of an examination. For instance, are we examining verification solutions for a large state with a complicated and interconnected nuclear fuel cycle? Or are we examining a smaller state with few nuclear explosive devices and a relatively rudimentary nuclear industry? What technologies are deployed by the state in weapons manufacturing? What specific industrial processes are in use? What is the rationale behind using them?

## Tools for a comprehensive, modular approach

It appears that nuclear disarmament verification work can benefit from an approach that is practical and results-oriented, provides a systematic knowledge-set of each disarmament activity and has a broad scope that enables the critical linkages between each activity to be defined and addressed. It should also be an approach that builds capacity among more actors to understand and participate in such verification.

One way to build such an approach is to investigate a wide range of disarmament scenarios, and test verification systems on them. Such an approach has several benefits. It can explore verification solutions for a large range of possible scenarios. It can also choose to develop scenarios that are appropriate for the particular question at hand. There is a spectrum of possible situations, ranging from those that are based entirely on more immediate issues, such as the DPRK's nuclear weapons programme, to more hypothetical future situations, involving large-scale reductions of nuclear weapons across the world. The hypothetical scenarios can help for readiness preparations, but also enable wider participation, since they can be isolated from political issues that might otherwise prevent stakeholders joining in. Such scenarios can also be used to test verification approaches for existing, but not yet realised, initiatives such as a Fissile Material Cut-Off Treaty. Whatever scenario is chosen, it must be internally-consistent, coherent and realistic.

Consequently, this report aims to provide initial guidance on:

- Developing and testing a comprehensive set of multilateral verification solutions for a wide range of possible disarmament situations;
- Enabling cost-effective, structured, capacity-building and awareness-raising exercises among stakeholders.

This approach is based on the development of nuclear disarmament scenarios and technical models of nuclear disarmament activities, and on their application in verification simulation exercises. This report is a guide to these concepts and discusses the questions that need to be addressed to ensure that any eventual system is comprehensive, trusted, reliable, and accessible.

This report begins by outlining key aspects of verification including its wider context and principles. It then considers equipment requirements for nuclear disarmament verification, and how stakeholders can work toward agreeing shared understandings and formal texts. Next, it lays out proposals for simulation exercises. Following this, it explains how to develop hypothetical disarmament scenarios and how to build models of the nuclear fuel cycles of the states involved in these scenarios.

## Section 1 endnotes

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3 M. Göttsche, M. Kütt, G. Neuneck and I. Niemeyer, 'Advancing Disarmament Verification: A Task for Europe?', *Non-Proliferation Papers*, No. 47, EU Non-Proliferation Consortium, October 2015, p. 10.

4 *Field Test FT-34: Demonstrated Destruction of Nuclear Weapons*, United States Arms Control and Disarmament Agency, January 1969. www.fas.org/nuke/guide/usa/cloudgap/ft-34.pdf.

5 T.B. Cochran, 'Black Sea Experiment Only a Start'. *Bulletin of the Atomic Scientists*, 45 (9), 1989, pp. 13-16.

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7 *Joint U.S.-U.K. Report on Technical Cooperation for Arms Control*, Office of Nonproliferation and Arms Control, Washington, DC: National Nuclear Security Administration, 2015.

8 'Member State Views on an IAEA Role in Verifying Nuclear Disarmament', *Verification Matters*, No. 10, London: VERTIC, 2015.

9 'The IAEA and Nuclear Disarmament Verification: A Primer', *Verification Matters, No. 11*, London: VERTIC, 2015.

10 M. Göttsche, M. Kütt, G. Neuneck and I. Niemeyer, 'Advancing Disarmament Verification: A Task for Europe?', *Non-Proliferation Papers*, No. 47, EU Non-Proliferation Consortium, October 2015, p. 16.

11 *Verification Technology Research and Development Needs*, US Department of State, 2013.

12 *Monitoring Nuclear Weapons and Nuclear Explosive Materials*. Washington, D.C.: National Academies Press, 2005.

13 *P5 Glossary of Key Nuclear Terms*, Beijing: China Atomic Energy Press, 2015.

# 2. Verification in Context

Verification is a difficult word to apply correctly. In its dictionary meaning, to verify something only means to engage in the process of establishing or demonstrating its truth, accuracy or validity. In arms control, verification is sometimes referred to as 'the process of gathering and analysing information to make a judgement about parties' compliance or non-compliance with an agreement'.[1] This use of the word ties the act of verifying to an agreement, and its concrete legal language. Nuclear disarmament verification therefore refers to a process or system that aims to build confidence among parties to a nuclear disarmament agreement that the terms of their agreement are being implemented effectively and fairly.

## What is being verified?

This raises the question: what might be involved in a nuclear disarmament agreement? At first glance, the meaning of nuclear 'disarmament' might seem obvious: the elimination of nuclear weapons within a single state, or within several states. Yet this does not indicate what is meant by 'disarmament' itself and what steps or processes are involved within it. The five nuclear-armed states under the NPT have defined nuclear disarmament as 'the process leading to the realization of a world without nuclear weapons and any measure contributing hereto.'[2] However, there are many different interpretations of what the process towards nuclear disarmament should involve, and therefore the measures that might be required to verify this process.

In 2000 states parties to the NPT agreed to 13 practical steps towards nuclear disarmament. These 13 steps provide the most comprehensive set of commitments that the nuclear weapon states have ever made on nuclear disarmament. Agreed measures towards nuclear disarmament include, among others: diminishing the role and significance of nuclear weapons in military doctrines; bilateral arms control between the US and Russia; unilateral reductions in nuclear arsenals; increasing transparency; reducing the operational status of nuclear weapons systems; and strengthening the verification regime for a world without nuclear weapons.[3] These steps were subsequently incorporated in an 'action plan' in 2010, which laid out 22 steps for the total elimination of nuclear weapons.[4]

Verifying that these political commitments have been carried out is a challenging task. Commitments to 'undertake further efforts' to eliminate nuclear weapons, or to 'promptly engage with a view to' achieving nuclear disarmament are vague, and determining whether a state has complied with these commitments is more a matter of political judgement than technical assessment.

While political commitments will always play a necessary role in any nuclear disarmament agreement, these will be strengthened by precise technical commitments relating to concrete disarmament activities. At the most general level, technical commitments in a future nuclear disarmament agreement could require parties to dismantle some or all of their nuclear weapons. This has traditionally been interpreted as the separation of nuclear materials in these weapons from the explosives that trigger a nuclear detonation. Verification in this sense would aim to confirm that these weapons have been dismantled, and that any attempt to avoid this commitment (or to later renege on it) would be detected.

However, the dismantlement of nuclear weapons may be only one aspect of a broader nuclear disarmament effort. More ambitious approaches to nuclear disarmament can involve:[5]

- Dismantling nuclear weapons;
- Terminating production of weapons-usable fissile material for nuclear weapons;
- Destroying or converting weapons-usable fissile material recovered from dismantled weapons or from stockpiles;
- Eliminating or reversing nuclear ‘weaponisation’ activities related to the development and maintenance of nuclear arsenals;[6] and/or
- Placing all remaining civilian nuclear materials and activities under international safeguards, including the monitoring of converted fissile materials recovered from dismantled weapons.[7]

This approach to nuclear disarmament, though more exhaustive, leaves a number of unanswered questions. How is ‘weapons-usable fissile material’ defined? What is involved in the ‘destruction’ or ‘conversion’ of such material? How exactly are the products of nuclear weaponisation activities eliminated? The precise technical procedures involved in nuclear disarmament are likely to vary between nuclear-armed states—whose nuclear weapon programmes differ in size, complexity, sophistication, and geographical distribution. Without a clear and common understanding of what has been agreed to, verification cannot provide useful indications of what constitutes compliance or non-compliance, and the precise wording of agreed disarmament commitments is a key contextual factor in the exploration of nuclear disarmament verification.

## Understanding ‘effective’ verification

Generally speaking, states tend to enter into agreements in good faith, with the intention of abiding by their obligations. However, when such vital matters as national security are involved, special assurances are needed that the parties will not engage in violating or circumventing their contracted commitments.

To this end, verification seeks three goals. First, it aims to provide timely and accurate indications of attempts to violate an agreement. In so doing, it serves another goal: the deterrence of violations. If a violation is likely to be met with a response that clearly outweighs the potential benefits of non-compliance, violating an agreement may not be appealing. Finally, verification aims to build confidence between parties and to assure them that their agreement is being implemented effectively and fairly. This can remove unnecessary doubts and suspicions, build broader trust between parties, and encourage other states to take up similar agreements.

Verification can be described as a circular process of collecting and analysing information on an actor's behaviour. Information can be collected via declarations or notifications, the use of agreed monitoring technologies or techniques (such as surveillance or inspections), or 'national technical means'. The analysis of this information aims to identify indicators of compliance or non-compliance, and inform potential responses. These responses can include consultations with the verified party, the recourse to alternative sources of information, or formal pronouncements of non-compliance. A list of typical verification procedures (and the tools used to carry them out) is given in Table 2.1 below.

**Table 2.1** Verification procedures and tools

| Procedure | Tool |
|---|---|
| Declarations of treaty-relevant materials and activities | ○ Initial (baseline) declarations, periodic (updated) declarations<br>○ Final declarations<br>○ Notifications |
| Monitoring to confirm declared materials and activities | ○ Direct observation<br>○ Examination of records/declarations<br>○ Indirect observation (sensors) |
| Monitoring to maintain continuity of knowledge of confirmed materials and activities | ○ Unique identifiers (tags)<br>○ Tamper-indicating seals<br>○ Design information verification<br>○ Surveillance |
| Monitoring to identify undeclared materials and activities | ○ National Technical Means (satellite imagery, intelligence)<br>○ Examination and comparison of records/declarations<br>○ Environmental sampling |
| Assessing compliance | ○ Inspection reports<br>○ Consultations<br>○ Further access/information<br>○ Dispute mechanisms<br>○ Non-compliance reporting mechanisms |

A verification system involves an arrangement of overlapping procedures and tools, with the product of one informing the application of others. Alone, each of these procedures can provide a useful, but incomplete, view of the implementation of an agreement. Together, they should form a coherent system which brings together a set of different tools and activities, including technical approaches, legal and political commitments, incentives for compliance, deterrence of noncompliance, and an acceptance of risks in a way that maximises the opportunity to overcome any single weakness in the system.[8]

The manner in which a verification system is designed depends entirely on what participants wish to achieve with it. Much has been written about what constitutes a satisfactory or effective verification system,[9] but this question cannot be answered in general. Standards of effective verification can only be gauged from the perspective of participating states. However, it is possible to identify two conflicting factors that shape verification.

The first factor is the perceived risk of undetected non-compliance, which is related to both the perceived likelihood of non-compliance and the consequences of such non-compliance going undetected. For instance, where a nuclear disarmament agreement prohibits the possession of any nuclear explosive device, a transgressor may achieve a significant military advantage by retaining an undetected nuclear arsenal. The severe consequences of this for compliant states could also be an incentive towards non-compliance,[10] maximising both the perceived likelihood and consequences of undetected non-compliance. In this case, a verification system might only be considered effective if it were extremely unlikely to miss indications of non-compliance.[11]

A second factor relates to the level of transparency a verified state is willing to tolerate. Information collected through a verification system may be susceptible to being used for non-verification-related purposes. It has long been acknowledged that in practice, ‘all kinds of verification require some degree of access to the national affairs or to the territory of the state being verified.’[12] The degree of access that a verified state would be prepared to accept would likely be limited by national security concerns (such as the protection of militarily-sensitive information), commercial concerns, domestic legislation (regarding both safety and security), and international legal requirements. The NPT is particularly important in this regard, as it obliges nuclear-weapon state parties not to transfer nuclear weapons to any persons whatsoever or assist non-nuclear-weapon states to acquire nuclear weapons.

Monitoring information is only useful when it can be reliably analysed and processed. Highly intrusive verification systems, that involve very sensitive monitoring equipment, may also degrade confidence between parties rather than build it. Monitoring equipment is rarely perfect, and a verification system must be able to distinguish between true and false indicators of non-compliance. Acting on false indications of non-compliance can have similarly significant consequences as failing to detect real instances of non-compliance.

Verification systems will also be limited by more than just intrusiveness: the cost of implementing verification (for both verifying and verified parties) can be considerable. The cost of inspection can relatively easily be ascertained through salary costs, the cost of equipment and operational costs, such as travel, lodging, administration and maintenance. However there are other costs too, which can be more difficult to quantify, such as the cost of being inspected. This often involves setting up and staffing national authorities, ensuring that they are equipped and endowed, financing an operational budget, and the costs to facility operators of hosting an inspection.

## Who is involved in verification and why?

While an observer can always draw their own assessment of an agreement's verification system, the most important assessment comes from those who are directly involved in verification. The perceived risks of non-compliance, and the level of intrusion required to balance this risk, can vary dramatically between states parties to an agreement.

All verified reductions of deployed nuclear weapons to date have been carried out between the US and Russia, where two parties are subject to the same commitments and both have recourse to the same verification system. Here, one state's demands for verification will be balanced by the knowledge that it will be subject to the same verification requirements. This may not be the case in the future. More inclusive approaches to verification can build confidence among a broader array of actors, and is consistent with the NPT (under which all states parties—not just NWS—have undertaken to pursue negotiations in good faith towards nuclear disarmament).[13]

More inclusive approaches to nuclear disarmament verification may take a number of forms. A reciprocal arrangement may emerge, in which a collection of nuclear-armed states develop a shared verification system that is implemented collectively. One (or more) nuclear-armed states may invite one non-nuclear-armed state,[14] or a collection of non-nuclear-armed states, to verify disarmament activities. Furthermore, one or more nuclear-armed states may allow an intergovernmental organisation—such as the IAEA—to verify disarmament activities on behalf of a collection of states.[15]

In each case, each stakeholder may have a different perspective on what an effective verification system might look like. Each stakeholder may perceive a different risk in undetected non-compliance, and while one might call for an extremely intrusive verification system, another might not consider certain measures and the associated expense in such a system to be necessary. Some may have a very detailed understanding of the technical procedures involved in nuclear disarmament activities, and a familiarity with the equipment that might be used to monitor these activities, whereas others may not.

In addition, a multilateral arrangement could present unique operational challenges. Personnel will likely have varied expertise and different clearance levels to examine sensitive data, which may necessitate the development of bespoke information-management and reporting procedures—both for field missions and for the ultimate evaluation and storage of information obtained during verification activities.

Accommodating differing requirements within a multilateral verifying party is not necessarily a new challenge. The IAEA has successfully verified aspects of nuclear disarmament in Iraq, South Africa, and Libya.[16] The US and Russia have both called upon the IAEA to verify an agreement between the two parties concerning the transfer of fissile materials from their military programmes to their civilian programmes. The diverse array of expertise offered by a wider range of verification stakeholders can generate new ideas and new perspectives on nuclear disarmament verification. Non-nuclear-weapon-states could contribute unique insights to overcome verification challenges that might be insurmountable in a more exclusive setting. Furthermore, a more inclusive approach to verification decreases the likelihood that any one participant might abuse the rights offered by a verification agreement. Verification participants can monitor each other, in addition to any nuclear disarmament activities being undertaken, to identify and respond to any improper behaviour. The verified state may therefore have more confidence that its transparency is not being abused for purposes beyond verification.

## The importance of examining verification in context

Effective verification is a subjective concept. As discussed above, a verification system is shaped and evaluated according to the context in which it will be used. While it is possible to discuss effective verification in an abstract sense, this often provides few insights as to how nuclear disarmament might be verified in the real world. Any attempt to understand how nuclear disarmament might be verified must take into account the disarmament activities involved, the states undertaking these activities, the relationships between these states and any verifying parties, and their perspectives on what would constitute effective verification in each case.

States unavoidably approach nuclear disarmament verification from their own perspective. Nuclear-armed states are predominantly concerned about the types of monitoring that might be applied to their infrastructure, what type of confidence they might get by applying such monitoring to other states, and how they might negotiate a satisfactory compromise. The current global context presents a number of pressing challenges in this regard. While a number of drafts exist for a Fissile Material Cut-Off Treaty (FMCT), there is little shared understanding about how such a treaty should be verified. Similarly, while both the US and Russia hope to extend their strategic arms control agreements into new areas (such as non-strategic nuclear weapons or strategic conventional weapons), neither have tabled any verification solutions. Disagreement over desirable nuclear disarmament activities and continued distrust between key stakeholders can make examining verification in the current global context politically challenging.

However, it is possible to consider nuclear disarmament in other contexts, which resemble the current global context, but differ in ways that facilitate (rather than complicate) the collaborative exploration of verification. Creating contextual 'boundary conditions'—which describe a hypothetical nuclear disarmament context—can provide a means of investigating key verification challenges without tackling the political and technical complications of reality. This approach has been adopted by the UK and Norway, whose on-going efforts to explore the involvement of non-nuclear-weapon states in disarmament verification incorporates a hypothetical disarmament context between two fictional states. This approach has also been adopted in the US, where fictional disarmament scenarios (including the removal of nuclear warheads from delivery vehicles and the continuous monitoring of stored nuclear warheads) have been proposed to guide technical research plans for nuclear disarmament verification.[17]

While it is vital to explore verification in context, it is not strictly necessary to explore it in the current context. Developing and exploring a variety of hypothetical disarmament scenarios can provide useful insights into the pressures that might shape effective verification in the real world. The application of these scenarios to the development and discussion of potential verification systems is discussed in Section 5. Section 6 describes how to develop a wide range of disarmament scenarios. Specific issues related to the role of equipment and shared understandings in verification activities are discussed in the following sections.

## Section 2 endnotes

1 *Coming to Terms with Security: a Handbook on Verification and Compliance*. Geneva: UNIDIR, 2003, p. 1.

2 *P5 Glossary of Key Nuclear Terms*, P5 Working Group on the Glossary of Key Nuclear Terms, Beijing: China Atomic Energy Press, April 2015, p. 2.

3 *Final Document of the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons*, NPT/CONF.2000/28, New York: UN, 2000.

4 *Final Document of the 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons*, NPT/CONF.2010/50, New York: UN, 2010.

5 David Cliff, Hassan Elbahtimy and Andreas Persbo, *Irreversibility in Nuclear Disarmament: Practical steps against nuclear rearmament*, VERTIC Report, London: VERTIC, September 2011.

6 Weaponisation activities can include 'weapon design, associated computer simulations, modelling and calculations, activities involving high-explosive lenses, high-energy electrical components, high-flux neutron generators, and implosion testing.' See J. Carlson, R. Leslie, A. Berriman, *Nuclear Weaponisation Activities: What is the Role of IAEA Safeguards?*, Australian Safeguards and Non-Proliferation Office, 2006.

7 *The IAEA and Nuclear Disarmament Verification: A Primer,* Verification Matters, No. 11, London: VERTIC, September 2015.

8 This is otherwise known as the 'Swiss cheese' view of verification, where individual aspects may have holes, but the sum of the parts is solid. Corey Hinderstein, 'Introduction', in Corey Hinderstein (Ed.), *Cultivating confidence: verification, monitoring, and enforcement for a world free of nuclear weapons*, California: Hoover Institution Press, 2010, p. xii.

9 See for example: Nancy Gallagher, *The Politics of Verification*, London: John Hopkins University Press, 1999; Allan S. Krass, *Verification: How Much is Enough?*, Stockholm: Stockholm International Peace Research Institute, 1985.

10 *Eliminating nuclear threats: a practical agenda for global policymakers*, International Commission on Nuclear Non-proliferation and Disarmament, 2009, p. 191.

11 This is a subjective judgement, and standards for effective verification could conceivably be lower. For instance, as nuclear disarmament progresses, the military value of nuclear weapons (and therefore the significance of non-compliance) may decrease rather than increase. Furthermore, the process of verifying nuclear disarmament may build trust between parties, making the perceived likelihood of violation lower towards the end of the process than at the start.

12 *Strategic Disarmament, Verification and National Security*, SIPRI, London: Taylor & Francis, 1977. pp. 22-23

13 *The IAEA and Nuclear Disarmament Verification: A Primer*, Verification Matters, No. 11, London: VERTIC, September 2015.

14 This scenario, which could be described as inclusive bilateral verification, is the focus of the UK-Norway Initiative described in sections 1, 3, and 5.

15 It is worth noting that the IAEA has both the statutory mandate to verify nuclear disarmament, and broad support for such a role among its member states. See: *Member State Views on an IAEA Role in Verifying Nuclear Disarmament*, Verification Matters, No. 10, London: VERTIC, September 2015.

16 It is important to note however that the IAEA failed to verify the ongoing peaceful nature of Iraq's nuclear programme to the satisfaction of some of its member states in the lead-up to the 2001 Iraq war.

17 See for example James Doyle, *Scenarios for Exercising Technical Approaches to Verified Nuclear Weapons Reductions*, LA-UR-10-02687, Los Alamos National Laboratory, April 2010.

# 3. Monitoring Equipment and Verification

Verification relies on an array of information to draw conclusions about compliance or non-compliance with an agreement. It is necessary to understand what has been agreed in order to determine whether a violation has occurred. Nuclear disarmament can involve many different activities, not all of which are well defined. It is also necessary to understand the relationships between the verifier and the verified, which brought such an agreement into existence. But perhaps most importantly, a verifier must have access to reliable information on the activities a verified state is, or is not, undertaking.

Effective monitoring can provide the evidence from which a compliance judgement can be made. The promise of effective verification can also encourage states to take on shared commitments in the first place. However, ineffective monitoring can degrade confidence rather than build it by producing false indications of compliance or non-compliance, or indeed no reliable indications at all. Without appropriate safeguards, monitoring tools can also be abused to collect information unrelated to the implementation of an agreement, such as commercially- or militarily-sensitive data. Consequently, doubts over monitoring capabilities can dissuade states from taking on shared commitments.

The equipment used to monitor and subsequently verify the implementation of a nuclear disarmament agreement must be accurate without being overly intrusive, unsafe, unreliable, or unwieldy. To achieve this, monitoring equipment is typically designed and developed for specific verification tasks. Much of this equipment has been transferred from non-nuclear uses—such as CCTV, tamper-indicating tags and seals—and adapted from 'off the shelf' products. Some nuclear agreements (such as the New START Treaty and the Nuclear Non-Proliferation Treaty) have instigated the development, testing, and production of a large array of bespoke monitoring equipment. These collaborative approaches to development help to build confidence that monitoring equipment:

- Is safe and secure to use, through a process referred to as 'certification';[1]
- Delivers the information required, through a process referred to as 'authentication'.

It is useful to consider what monitoring challenges might be presented by nuclear disarmament verification, what equipment is currently available, and what equipment might have to be developed or adapted to overcome these challenges. It is particularly important to consider how such equipment can be used in a multilateral environment, in which the range of actors may place different demands on monitoring equipment, and generate a variety of safety and security concerns. Convincing all parties within a multilateral effort to verify nuclear disarmament that equipment provides the right information, and only the right information (that it is *authentic*), is a key challenge.

This section explores the equipment requirements and restrictions presented by a selection of generic monitoring tasks associated with verifying nuclear disarmament. These tasks include:

- Confirming the identity of declared treaty-accountable items (TAI), such as nuclear warheads or containers of nuclear material.
- Confirming that treaty-relevant processes occur as declared.
- Maintaining continuity-of-knowledge of treaty-accountable items and processes in circumstances where continuous monitoring is unavailable.
- Detecting attempts to hide TAIs or treaty-relevant processes.

## 3.1 Equipment for confirming the identity of declared items

### Treaty Accountable Items (TAIs)

Nuclear arms control agreements place great emphasis on tracking and accounting for items or objects. For example, the New START Treaty between the US and Russia limits the number of nuclear weapon delivery systems each party can deploy, and the total number of nuclear warheads deployed on these delivery systems. Each party implements the agreement by limiting and accounting for these ‘treaty accountable items’ (TAIs), and each party can verify this accounting by observing and counting deployed delivery systems and confirming the number of warheads each system is armed with.

Nuclear disarmament will also involve controlling and accounting for the many items that make up a nuclear weapons programme. For example, a nuclear disarmament agreement may require the dismantlement of nuclear warheads, the disposition of fissile material ‘pits’ from these warheads, and the destruction of non-nuclear components from dismantled weapons (as discussed in Section 6.2.7). Verifying nuclear disarmament therefore requires the ability to confirm that an object being dismantled is indeed a nuclear warhead, or the ability to confirm that a stored object is indeed a fissile material ‘pit’ removed from a warhead.

## Identifying characteristics

Confirming the identity of a TAI rests on a shared and precise understanding of what that item actually is. Any identifying characteristics must be precise enough to discriminate between a treaty accountable item and similar, but unaccountable, items and capable of being measured by a verifying party. However, information on the precise composition of many of the items involved in nuclear disarmament (such as nuclear warheads, fissile material 'pits', and other nuclear weapon components) is likely to be proliferative or sensitive. As such, identifying characteristics often have to be reduced to a range of attributes (such as the rough proportions of fissile isotopes in nuclear material) or to a 'template' of a single known item.

Non-nuclear materials (such as weapon delivery systems, reactor components,[2] or non-nuclear components of nuclear weapons) can be identified by their chemical composition, weight, and appearance. Nuclear materials are typically identified by their characteristic radioactive emissions. Radioactive materials can emit particles known as 'alpha' particles, 'beta' particles, and neutrons. These materials can also emit electromagnetic energy in the form of 'gamma' radiation. The types, amounts, and energies of these emissions are related to the types and quantities of nuclear material present. For example, the gamma rays produced by plutonium can help identify whether the isotopes present are consistent with weapons-usable plutonium. Measurements of plutonium gamma rays can also be combined with measurements of neutron emissions to infer the mass of the isotopes, which can help identify whether the quantity of weapons-usable plutonium is consistent with a nuclear weapon.[3]

## Equipment requirements and operational parameters

The identifying characteristics of nuclear items are typically measured using passive non-destructive assay (NDA) equipment, which detect direct or secondary emissions from radioactive objects.[4] The IAEA uses more than 100 different NDA systems to verify the identity of nuclear items or materials while carrying out its safeguards activities. According to the agency's publication *Safeguards Techniques and Equipment*, these systems range from small portable gamma ray detectors[5] (designed primarily to identify types of nuclear material) to large combined gamma ray and neutron detectors (designed to identify both the isotopic composition and mass of nuclear materials).[6]

Each piece of NDA equipment is designed to measure selected identifying characteristics of nuclear material within certain operational constraints. These constraints can relate to the nature of the material being measured, or to the circumstances in which it is typically measured. For instance, spent reactor fuel assemblies are highly radioactive and must be stored underwater to keep them cool. As such, the nature of these items can only be confirmed by equipment that can accommodate powerful radioactive signals, and can be used remotely underwater. Other operational constraints can include the physical size of measured materials, the time required to measure these materials, and the level of expertise of equipment operators. These operational constraints mean that while many of these NDA systems could be used in principle to confirm the identity of TAIs involved in nuclear disarmament, it is not yet clear whether they would be suitable in practice.

## Proliferation and sensitivity constraints

Many of the identifying characteristics of TAIs involved in nuclear disarmament are inherently proliferative or sensitive. Domestic constraints (such as information control regulations) and international obligations (such as the NPT) can prevent a nuclear-armed state from communicating the characteristics that can distinguish a nuclear weapon from other collections of nuclear and non-nuclear components. Similar obligations can prevent a verifying party from receiving such information, either from a declaration by a disarming state or through measurements of TAIs.

These constraints can be overcome by communicating the identifying characteristics of any TAIs through broad attributes, or through the creation of a 'template' through a known TAI (as discussed above). So-called 'information barriers' can be integrated into equipment to translate sensitive or proliferative measurements into a judgement of consistency with expected templates or attributes. A number of information barrier systems have been developed to identify uranium or plutonium with isotopic compositions consistent with a nuclear weapon.[7] Proliferation and sensitivity constraints vary depending on the items being identified and the context in which they are being identified. The characteristics of items that are used in (or removed from) nuclear weapons are likely to be more proliferative or sensitive than the characteristics of items that are not directly usable in a nuclear weapon. Furthermore, each nuclear-armed state may have differing views and regulations concerning the sensitivity of these items. Unique information barriers may therefore have to be developed for individual verification tasks, within individual disarmament agreements. This may be relevant particularly in cases of multilateral verification of disarmament, where the variety of states involved in verification may have differing views over the levels of measurement accuracy required, and may present further complexity regarding the communication or release of sensitive information.

## Safety constraints

The materials and processes involved in nuclear disarmament present a number of safety concerns that are not typically encountered during the verification of IAEA safeguards. Equipment that might be safe to use in a nuclear fuel processing facility may not be suitable for use in a nuclear weapon dismantlement facility or nuclear component disposition facility.

For example, a verifying party may wish to use a neutron detector that relies on pressurised tubes of helium-3 gas, high voltage power supplies, and polyethylene shrouding to confirm the identity of plutonium removed from a nuclear weapon. Safety risks presented by this scenario could include:

- A criticality hazard. Polyethylene is used in this detector to slow neutrons down to increase the probability of detection. This effect can also increase the risk that decelerated neutrons will prompt a criticality in the plutonium sample.
- A fire hazard. Polyethylene is also flammable, and its introduction could create an unacceptable addition to the fire hazard in facilities that contain similarly hazardous materials.
- An electrical hazard. The high voltage power supply can present a risk of electrical shocks to personnel, and to other items of equipment in the surrounding area. In the presence of high explosives (such as those used within nuclear weapons), electric discharges could trigger an explosion.

The standards by which equipment is judged to be safe for use will depend on the characteristics of the environment in which it will be used. In many cases, a nuclear-armed state may be legally obliged by domestic legislation to enforce these standards, which may or may not be set by those that typically work with any relevant TAIs. Any new or adapted equipment for confirming the identity of TAIs involved in nuclear disarmament would likely have to be examined by a disarming state before they can be approved for use.

### Other operational constraints

TAIs associated with nuclear disarmament may be large, cumbersome, or inaccessible. TAIs such as nuclear weapons or weapon components may have to be placed within containers to block the release of proliferative or sensitive information, as well as harmful radiation. Equipment for confirming the identity of a TAI may have to be designed to penetrate or accommodate these physical barriers.[8] Safety concerns as well as security concerns would typically prevent a verifying party from touching or moving a TAI. In these cases, identifying equipment must be portable enough to be moved around the TAI, rather than a TAI being moved to the equipment.[9] Finally, security concerns may limit the number of operators permitted within any one location. Identifying equipment may therefore have to be usable by a small team of personnel.

## 3.2 Equipment for confirming the nature of disarmament processes

### Verifying processes

Arms control and disarmament agreements can include a number of different obligations related to the development, manufacture, maintenance, storage, and disposal of nuclear-related items. For instance, a disarmament agreement might require a state to dismantle nuclear weapons, transform their components into forms that cannot be re-used in nuclear weapons, and renounce the construction of further nuclear weapon components.

These obligations could be verified purely by identifying and characterising the items that enter or emerge from these processes (as discussed in Section 3.1). However, verification of these disarmament obligations can be strengthened by also examining the technologies or techniques that underpin the processing of such items.

Restricting the operational parameters of these technologies or techniques (and verifying that these restrictions remain in place) can make it easier to identify and characterise the items they focus on, and can build additional confidence that a disarmament agreement is not being violated. The use of Design Information Verification (DIV) inspections under Comprehensive Safeguards Agreements with the IAEA is an illustrative example. By verifying the designs of nuclear facilities, the IAEA can improve the design of its nuclear material accounting verification techniques and identify attempts to misuse these facilities for undeclared activities.[10]

## Identifying characteristics

The identifying characteristics of nuclear disarmament processes can be communicated through layouts or blueprints of facilities and technical specifications of the technologies or techniques involved. In the case of Comprehensive Safeguards Agreements with the IAEA, this information is transmitted through a standardised Design Information Questionnaire. The information required to identify a research reactor includes, among other aspects: the type, weight, chemical form, and configuration of reactor fuel elements; the procedures for loading, unloading, and moving fuel elements; the location of accountancy measurement points; and the techniques used to maintain internal accounts.

A disarming state may communicate the characteristics of disarmament processes to a verifying party through similar techniques. However, it is not yet entirely clear which aspects of a disarmament process would be most relevant to understanding (and ultimately verifying) whether this process conforms with any disarmament obligations. In contrast, the processes involved in operating research reactors, or other common civilian nuclear processes, are well understood. The IAEA can call on a broad array of expertise to translate the information contained within a Design Information Questionnaire into an assessment of the proliferation risks of a given civilian facility. This may not be the case for multilateral approaches to disarmament verification, where the processes involved in nuclear armament and disarmament can vary considerably from state to state, and where the knowledge of these processes is rare.

## Equipment requirements and constraints

The equipment required to confirm the nature of a disarmament process depends on the complexity of the process and the technologies involved. Separating the physics package of a nuclear weapon from its weapon casing may be carried out using a small range of hand tools and winches. If a verifying party can confirm the identity of a nuclear weapon entering this process and the identity of components emerging from it (as discussed in Section 3.1), the separation process can be confirmed by checking that no substitute weapon or components have been clandestinely introduced or removed. This could be achieved by scanning for substitute items before and after the separation process, and by sealing or monitoring access points. For example, the UK-Norway Initiative used hand-held radiation detectors (such as the HM-5 gamma ray spectrometer) to sweep a declared warhead dismantlement area, and tamper-indicating seals to block access points.

In contrast, the technologies involved in processing and converting nuclear materials are complex. If a disarming state commits not to produce any further weapons-usable nuclear material, it may be challenging to confirm that all items leaving a nuclear material processing facility are not weapons-usable. Similarly, if a disarming state commits to adjusting such a facility so that it cannot produce weapons-usable material, it may be challenging to monitor every aspect of this facility to confirm that this remains the case. These adjustments may be minor and easily reversed. The IAEA can call on 3-D laser range finders to map the physical layout of complex systems to within a millimetre, and compare scans to identify any structural changes. As discussed above, applying this technology to nuclear disarmament verification requires an understanding of what system changes might be involved in a nuclear disarmament agreement.

## Proliferation and sensitivity constraints

As discussed in Section 3.1, examining the items involved in nuclear disarmament may expose a verifying party to proliferative or sensitive information. These concerns also apply to the processes involved in nuclear disarmament. The non-proliferation obligations of NWS and NNWS under the NPT may prevent the former from allowing the latter to directly observe the dismantlement of nuclear weapons, or the technologies involved in constructing or processing nuclear weapon components. As such, equipment such as surveillance cameras or 3-D laser range finders may have limited application in verifying nuclear disarmament processes.

The effect of these constraints on the monitoring of nuclear weapon dismantlement has been explored by the UK-Norway Initiative, which restricted the application of surveillance cameras to views of insensitive entrances and exits. The effect of these constraints on other nuclear disarmament activities (such as fissile material component fabrication and disposition) requires further study.

## Intrusiveness and obstruction

The proliferation and sensitivity constraints described above place a great emphasis on equipment such as tamper-indicating tags and seals. These can identify the movement or alteration of certain technologies or areas without revealing proliferative or sensitive information. However, the application of such equipment can obstruct disarmament processes by requiring the verified removal and reapplication of tags and seals every time technologies or areas are used. Similarly, sealing off dual-use technologies (that could be used equally for prohibited and allowed processes) can disrupt legitimate and peaceful uses of facilities. While surveillance cameras can monitor disarmament processes in real-time, they can also collect information on other processes unrelated to disarmament.

With these concerns in mind, equipment for verifying disarmament processes must be applied in a manner that minimises the disruption of these processes, and any other legitimate processes that may occur in a disarming state. Nuclear disarmament may involve an array of processes, and the technologies used in these processes will vary from state to state, and from facility to facility. As such, a system of tags and seals that is acceptable in one instance may not be acceptable in another. Acceptable solutions for monitoring nuclear processes (whether for non-proliferation or for disarmament) must be developed in collaboration between verifying parties and verified states.

## 3.3 Equipment for maintaining continuity of knowledge on items and processes

### Keeping track of items and processes

Nuclear disarmament agreements can oblige states to contain or track certain items, as well as to undertake—or refrain from undertaking—certain processes. Sections 3.1 and 3.2 outline some of the techniques and equipment that can be used to verify that these obligations have been met. However, some of the techniques described in those sections cannot be applied continuously throughout the duration of a disarmament agreement: inspectors cannot be present to confirm and re-confirm the identity of items or the nature of processes all of the time.

With this in mind, a nuclear disarmament verification agreement might include provisions for maintaining 'continuity of knowledge', which would identify any alterations or substitutions to items or processes once they have been confirmed by inspectors. For example, while IAEA inspectors can use NDA equipment (discussed in section 3.1) to confirm the quantity of uranium in a storage container, repeating this process on a regular basis would be inefficient. Rather, once the storage container has been examined, inspectors can maintain continuity of knowledge by adding a unique tag to the container and sealing it. The former allows inspectors to recognise an individual container, while the latter would indicate whether its contents have changed since it was last examined.

This principle may be applicable in most aspects of nuclear disarmament verification. If a verification party is able to confirm that a nuclear weapon has been removed from its delivery vehicle, continuity of knowledge could allow verifiers to track that weapon from its deployment site to a dismantlement facility without having to examine the weapon itself. Similarly, applying continuity of knowledge techniques to a known nuclear weapon dismantlement process would allow a verifying party to quickly identify any changes to that process, without having to examine the entire process again.

## Identifying characteristics

A verifying party can maintain continuity of knowledge for a known item or process by simply sustaining visual contact. However, equipment or technology can provide continuity of knowledge in a less demanding way by applying unique identifying tags to an item or process that cannot be easily removed or replicated, and by indicating whether aspects of this item or process have been accessed or changed. Tags and seals must work together to provide continuity of knowledge: a seal must be associated with a unique tag otherwise it could be broken and replaced with a substitute.

Unique identifying tags can be as simple as a barcode or serial number applied to a container. However, these can be easily replicated and applied to substitute containers to break continuity of knowledge. More sophisticated techniques include tamper-indicating reflective particle tags that apply unique patterns of particles to surfaces, and intrinsic tagging which examines an object itself to identify and record unique microstructures that cannot be easily replicated.

The sophistication of tamper-indicating seals can also vary, from single-use metal caps and adhesive sealing tapes to reusable fibre-optic and radio-frequency seals. Some of these seals (such as single-use metal caps) can be applied to a variety of objects, including containers, cabinets, and other equipment. Some are purpose-built, such as the JRC CANDU sealing system to identify access to spent CANDU reactor fuel bundles.[11] These seals can be augmented with scanning equipment, such as laser surface mappers, to identify any attempts to alter an object without disturbing a seal.

## Equipment requirements and constraints

The IAEA, in collaboration with its member states, has developed and certified several tags and seals systems for providing continuity of knowledge during its safeguards activities in NNWS. Verifying nuclear disarmament will involve tracking and sealing a number of unfamiliar objects. Few individuals know about the precise design of nuclear weapons, their containers, and the technologies used to store, move and modify them. While nuclear-armed states have domestic systems for identifying, tracking, and sealing these objects, they may be unable or unwilling to share these systems with a potential verifying party. While verifying nuclear disarmament will likely involve tracking and sealing many familiar objects (such as fissile material containers) too, new constraints could complicate the delivery of continuity of knowledge through such familiar systems.

## Security constraints

The nuclear materials identified and tracked through IAEA safeguards do not present the same security risks as items involved in nuclear disarmament. IAEA inspectors may be allowed to touch, move, and apply tags and seals (either directly or remotely) to fresh reactor fuel bundles, nuclear material containers, and equipment. This may not be the case for containers holding nuclear weapons or nuclear materials removed from weapons. National security requirements may prevent anyone other than domestically-approved individuals from having any contact with such items, or even from approaching such items.

This introduces a challenge to maintaining continuity of knowledge of particularly sensitive items involved in nuclear disarmament. Tags and seals are only effective if they are applied in the correct way, and a verifying party may not be confident that this would be the case if only a disarming state were able to apply them. This may not be a concern for established tagging and sealing equipment, where all parties will have a shared knowledge of correct application procedures. However, novel tagging and sealing equipment may exacerbate these concerns—particularly if they are developed and produced predominantly by a disarming nation.

## Accessibility

A verifying party must be able to access tags and seals to confirm the identity of an object and understand whether it has been altered and accessed. This may be challenging if relevant objects are stored in constrained environments, or cannot be easily moved or rearranged to provide access.

While tags and seals are not typically designed to prevent a verified state from accessing or altering objects, they are meant to provide prompt indication if this has occurred. What is considered ‘prompt’ for IAEA safeguards may not be prompt enough for the verification of nuclear disarmament. Many of the IAEA’s seals must be removed from objects and returned to IAEA headquarters in Vienna for examination before they can indicate whether the object has been accessed and altered. If the object concerned is a single low-enriched uranium fuel assembly, this delay might be acceptable. If the object is a vital nuclear weapon component, such a delay may not be acceptable.

Remote access technologies, which communicate with tags and seals to ascertain information, may be able to provide a verification party with swift and indirect continuity of knowledge. Such technology is currently used by the IAEA in its regular safeguards activities. A verifying party will need to be confident that a disarming state cannot spoof or disrupt such communication technology, and a disarming state will need to be confident that these communications do not disrupt other unrelated activities or transfer unrelated information.

### Intrusiveness and obstruction

The application of tags and seals can obstruct disarmament processes if they must be frequently removed and reapplied (as discussed in section 3.2). They can also disrupt legitimate activities if they are applied to dual-use objects or technologies that could be used for permitted applications. Continuity of knowledge through the application of tags and seals would need to be undertaken in a manner that minimises the disruption of these processes, and any other legitimate processes that may occur in a disarming state.

## 3.4 Equipment for detecting undeclared items and processes

### Detecting hidden items or processes

Arms control and disarmament agreements typically require participating states to declare all weapons, sites, and facilities that are subject to control, either as a transparency measure or to facilitate verification. These declarations help participating states to design and implement verification systems to identify if these items and processes are being used in ways that contravene the agreement. States typically enter into such agreements with the intention of honouring them fully. Verification systems typically focus on investigating declared items and processes to build confidence that this is the case. The preceding sections (3.1, 3.2, and 3.3) reflect this by discussing equipment that is typically used to investigate the nature of declared items or processes.

However, not all states enter into agreements with the intention of honouring them. Such states may be tempted to hide the misuse of items or processes from a verifying party by failing to declare and present them for verification.[12] This risk may seem particularly acute for nuclear disarmament verification, where the undeclared retention of a single nuclear weapon could have significant implications for those honouring their disarmament commitments. To counter this risk, most arms control and non-proliferation verification systems contain some mechanism for detecting undeclared items and processes. Any nuclear disarmament agreement would need similar, if not stronger, mechanisms to build confidence that parties are declaring and presenting all relevant items and processes.

### Identifying characteristics

Nuclear disarmament agreements will probably focus on controlling nuclear materials, either in their weapons-usable end-form or the activities that can generate this form (such as spent fuel reprocessing or uranium enrichment). As such, the equipment described in Sections 3.1 and 3.2 above can be used to determine whether a suspicious item or process should have been declared under a disarmament agreement. In this sense, detecting undeclared items or processes involves applying many of the same tools for characterising declared items or processes. However, a verifying party must first know where to look for suspicious items or processes.

A disarming state has a number of opportunities to conceal items or activities that it might be required to declare under a disarmament agreement. Many processes that might be covered by a disarmament agreement can be carried out in small unobtrusive locations. While producing weapons-usable plutonium may require large-scale reactors and spent fuel reprocessing facilities, this plutonium can then be integrated into a weapon in small dual-use facilities dispersed around a state. Gas centrifuge plants—that can enrich uranium to a point where it can be used in a nuclear weapon—also have a small footprint and can be hard to detect. Similarly, disarmament-relevant items—including nuclear weapon components and nuclear weapons themselves—can be hidden in a number of locations. Thick heavy shielding materials, such as lead containers, can block most of the characteristic radiation signatures discussed in Section 3.1.

It is consequently challenging to establish a set of unambiguous characteristics that could enable a verifying party to find indications of undeclared items and processes. Instead, verifying the absence of undeclared items or processes would likely involve integrating information from a variety of equipment to gain an overview of the completeness of a disarming state's declarations, and to guide further investigations. These investigations might involve requesting further information about suspect sites, or even on-site inspections. These activities may be interpreted as confrontational, and the risks of creating false impressions of undeclared items or processes can seriously degrade the confidence that verification aims to produce. As such, these information integration systems need to be carefully designed. The IAEA and its member states have developed equipment and systems for verifying the completeness of NNWS declarations under the NPT. As was the case in Sections 3.1, 3.2, and 3.3, aspects of these systems can be adapted to verify the completeness of a state's disarmament declarations.

## Equipment requirements and constraints

There is one general requirement that shapes the nature of equipment that is used to detect undeclared items and processes: they must collect a broad range (either geographically or thematically, or both) of information and present it in a comparable manner. The IAEA's 'information-driven' safeguards draws on information collected through the verification of *declared* items and processes; the examination of commercial satellite imagery; the examination of open-source information (including import and export information); and third-party information.[13] In some cases, the IAEA can also use 'wide-area environmental sampling'.[14] Using this technique, the agency can take samples from areas as large as hundreds of thousands of square kilometres to look for undeclared nuclear materials or activities.[15] These techniques use entirely different forms of equipment, but the information they produce can be integrated with others to enhance an impression of the completeness of a state's declarations.

A similar system of measuring equipment and information processing would likely be used to verify the completeness of a disarming state's declarations. A verifying party would therefore be able to draw on satellite imagery, environmental sampling, open sources of information, and the clandestine intelligence-gathering capabilities of participating states. However, some aspects of nuclear disarmament verification suggest that the design and implementation of such a system would be subject to a number of notable constraints.

## False indications of undeclared items and processes

As discussed above (and in Section 2), the demands placed on verification by parties to a disarmament agreement depend on the specific consequences of non-compliance with that agreement. For example, a failure to properly declare nuclear materials or activities through a safeguards agreement with the IAEA does not immediately equate to a nuclear threat to other states. However, a state's failure to declare and disarm a collection of nuclear weapons as part of a multilateral nuclear disarmament agreement might present a very severe threat to other disarming parties. As such, states parties may feel pressured to respond to indications of incomplete declarations in a similar manner to *proof* of incomplete declarations.

This political dynamic creates a technical dilemma. While equipment used to identify undeclared items and processes would have to be sensitive to almost any indication of incomplete declarations, it would also have to carefully sift out any false indications of incomplete declarations. While this dilemma is not unique to nuclear disarmament verification, it may be felt more keenly here than in the verification of non-proliferation.

## Intrusiveness

As identified in Sections 3.1, 3.2, and 3.3, attempts to verify nuclear disarmament may disrupt or complicate legitimate activities in a disarming state. This can be minimised at known sites by designing a verification system in a manner that accommodates the processes that occur there. This approach is adopted by the IAEA, which uses ad-hoc inspections at facilities to design and negotiate the precise application of verification techniques with the state in question.

However, there is little opportunity for such preparation if the facility in question has not been declared. A verifying party may identify a facility of interest with little idea of what processes actually occur within, or how it might best investigate that facility without disrupting these activities. Complementary access inspections—

conducted by the IAEA in states with an Additional Protocol to a safeguards agreement in force—can in some circumstances take place with less than two hours' notice. States hosting a complementary access inspection can manage the access of inspectors to prevent the dissemination of sensitive information and to minimise complications due to safety and security concerns.

While these 'managed access' procedures could be available to a disarming state in principle, applying them in practice to minimise the intrusion of inspections could be challenging. Nuclear disarmament—and more importantly nuclear armament—is likely to involve activities at military sites. For example, a nuclear-armed state may develop high explosive lenses for its nuclear weapons within the same complex that it develops high explosives for conventional purposes. The safety and security concerns at these sites are likely to be far greater than at the civilian sites that are at the focus of the IAEA's complementary access inspections. Managing the access of inspectors searching for undeclared nuclear activities at a military site is likely to be very complicated.[16]

## 3.5 Developing equipment for nuclear disarmament verification

The IAEA and its member states have developed a large array of monitoring equipment that facilitates the verification of nuclear non-proliferation. This equipment has been developed over a long period of time and according to a continuously updated research and development strategy, to address specific verification tasks. Many of the tasks involved in verifying nuclear non-proliferation will also be involved in verifying nuclear disarmament. Much of the existing toolkit of monitoring equipment described in Section 3 (and in the IAEA's own publications) will therefore be applicable to nuclear disarmament verification.

However, nuclear disarmament presents a number of monitoring challenges that suggests that this toolkit will have to be expanded or adapted. These challenges include the safety and security risks of monitoring nuclear disarmament (see Section 3.1), the release of proliferative information during disarmament (see Section 3.2), the disruption of ongoing peaceful activities (see Section 3.3), and the consequences of ineffective monitoring (see Section 3.4).

Nuclear-armed states may be unsupportive of multilaterally-verified nuclear disarmament unless they are confident that effective monitoring equipment exists (or will exist) to achieve it. However, it seems likely that only the far-sighted will engage in developing such equipment now, without clearer and more immediate disarmament missions to engage in, particularly if that pursuit comes at the expense of an improved toolkit for monitoring nuclear non-proliferation. But existing bilateral and multilateral equipment development strategies can provide insights into how this dilemma might be overcome.

## Equipment development for nuclear disarmament verification

Some nuclear-armed states have been considering how they might demonstrate reductions in their nuclear stockpiles through bilateral or multilateral verification agreements for some time. A large part of their efforts to date have been devoted to developing new monitoring equipment that could be used to verify specific disarmament activities.

The US has been responsible for the most extensive explorations of nuclear disarmament verification techniques to date. These explorations began in earnest at the close of the Cold War in 1991, when the US formed a Warhead Dismantlement and Fissile Material Control Advisory Committee that sought to explore methods for reporting and demonstrating warhead dismantlement.[17] By the latter half of the 1990s, the US had created a dedicated nuclear warhead dismantlement verification and fissile material control technology programme, as well as a warhead dismantlement study group, through what is now the US National Nuclear Security Administration (NNSA).

These efforts have produced and demonstrated several types of verification equipment relevant to nuclear disarmament. This includes equipment designed to maintain continuity of knowledge (see Section 3.3) on nuclear warheads and warhead-related items, and bespoke scanning equipment for identifying and characterising nuclear warheads and warhead-related items (as discussed in Section 3.1). The US has also developed a number of information barrier technologies that can process the outputs of scanning equipment, including a ‘Controlled Intrusiveness Verification Technology’ (CIVET), the ‘Trusted Radiation Attribute Demonstration System’ (TRADS), the ‘Trusted Radiation Inspection System’ (TRIS), and the ‘Attribute Measurement System’ (AMS). All these systems aimed to confirm the identity of a nuclear weapon without releasing proliferative information. However, it was acknowledged at the time both by scientists involved in these programmes and by policymakers that this equipment could only be successfully implemented in an arms control or disarmament agreement if they were developed cooperatively by all parties to that agreement.[18]

With this in mind, the US and Russia began working together to explore nuclear disarmament verification technologies throughout the 1990s. The joint US-Russia Warhead Safety and Security Exchange Agreement entered into force in 1995, and allowed both parties to explore how radiation detection equipment could be used to identify classified nuclear warhead items without releasing classified information. Similarly, the US and Russia collaborated to explore how fissile material removed from dismantled Russian nuclear weapons could be verifiably stored at the jointly-constructed Mayak Fissile Material Storage Facility in Russia. As part of this project, the US demonstrated the Attribute Measurement System (and integrated information barrier) to a visiting Russian delegation.

This work overlapped with that of the Trilateral Initiative, which brought the IAEA into the ongoing collaboration between the US and Russia on the verified disposition of fissile materials emerging from dismantled nuclear weapons. Over the course of 98 meetings, the initiative conducted a thorough survey of current measurement equipment (starting with approved IAEA equipment), and gradually developed an agreed measurement methodology, including a statement of equipment requirements. This was translated into detailed functional specifications and designs, which informed the creation and demonstration of prototype equipment.

The introduction of the IAEA—a multilateral actor—raised the risk that information relating to nuclear weapons might be released to non-nuclear-weapon states (NNWS) members of the agency in violation of the NPT. The inclusion of the IAEA therefore created new equipment restraints, but also opened the equipment development process up to new actors. The development process incorporated technical workshops in Italy, Japan and the UK, and demonstrated how nuclear-armed states might collaborate with each other, as well as the IAEA and its member states to develop equipment for verifying nuclear disarmament activities.

The UK—which also collaborates with the US in the exploration of disarmament verification technologies—is also exploring verification equipment constraints related to nuclear non-proliferation in partnership with Norway, a non-nuclear-weapon state under the NPT. The 'UK-Norway Initiative' seeks to investigate the technical and procedural challenges in verifying the dismantlement of nuclear weapons. Part of this initiative has involved the joint development of an 'information barrier' system, that aims to prevent the release of proliferative information while verifying the nature of a nuclear weapon (as discussed in Section 3.1).

Both the UK and Norway developed their own information barriers according to a joint design. These barriers were tested independently according to an agreed programme, before being introduced to exercises to assess their performance. The initiative suggested that there is value in developing and testing generic monitoring equipment against specific verification tasks to identify any equipment challenges and possible mitigation strategies. It also suggested that a joint design process—incorporating shared views on tasks, requirements, and constraints—can help to ensure that parties have confidence in the equipment.

Verification equipment development studies conducted to date suggest that technologies do exist that can help verify the dismantlement of nuclear weapons and the subsequent disposition of nuclear materials. However, according to a US expert involved in some of these efforts, much remains to be done to refine these technologies and to provide assurances to all parties that they can produce authentic and trustworthy results.[19]

## Equipment development for nuclear non-proliferation verification

The equipment development processes outlined above focussed on creating tools to carry out specific verification tasks. They have demonstrated how nuclear-armed and non-nuclear armed states, as well as the IAEA, can generate equipment according to jointly-agreed requirements and designs. Nevertheless, a broad large-scale development plan can provide strategic vision, coordinate efforts, and also inform and incentivise smaller more focussed development programmes. The IAEA's Strategic Equipment Development Plan is a good example of this approach.

The IAEA Department of Safeguards Long-Term R&D Plan (2012-2023) outlines an equipment development strategy,[20] with the goal of improving their technical capabilities and enhancing their readiness to verify the peaceful uses of new nuclear technologies and to support new verification missions. The department implements this strategy by creating a set of user requirements and operating criteria for specific types of equipment, such as non-destructive assay, seals, and surveillance. These requirements are then conveyed to equipment developers within member states, who design and build verification tools according to these requirements. The IAEA and the developer then put the equipment through a series of tests to establish whether it performs as expected and meets all design requirements. If equipment passes these tests, it can be certified by the IAEA as suitable for application in the field.

## An equipment development strategy for nuclear disarmament verification

The IAEA and its member states have demonstrated their equipment development capabilities. These could be applied to overcoming the equipment challenges outlined in Sections 3.1, 3.2, 3.3, and 3.4.

An option presented by former IAEA staff that participated in the Trilateral Initiative would involve creating an IAEA Centre for Disarmament Verification Research and Development. According to their report, this centre would direct the development of verification equipment through specific categories of work. These include generic research into verification concepts and approaches, the development of prototype equipment, the creation and exploration of 'mock-up verification arrangements', the development of procurement policies (including equipment specifications and selection procedures), and the creation of teams to support state-specific implementation of such equipment. The report suggests that this centre should be located within or close to the IAEA in Vienna, and should serve as a hub for disarmament verification research and development. Members of a nuclear disarmament verification network in Germany have also proposed a similar EU Centre for Disarmament Verification, which would aim to coordinate and communicate individual equipment development efforts within the European Union.[21]

## Section 3 endnotes

[1] Nuclear disarmament can involve extremely sensitive facilities and activities—including those that are directly involved in the manufacture of nuclear weapons. A verified party is likely to place extremely stringent requirements on this certification process.

[2] Such as moderators including graphite or heavy water.

[3] Gamma and neutron emissions can also help identify the isotopic composition and mass of uranium. However, the low emission of gamma rays from uranium makes it challenging to detect a useful radioactive signature without actively encouraging these emissions.

4 This equipment typically relies on measurements of gamma ray and neutron emissions. Alpha and beta particles can help identify a radioactive object, but are too easily scattered or absorbed by materials (including any storage cases or equipment cases) to be particularly useful. Other non-destructive assay techniques measure by-products of this radiation (such as Cherenkov Radiation detectors, for example) and other observable quantities (such as weight or volume).

5 Such as the HM-5 field spectrometer.

6 Such as the Fork Detector irradiated fuel measuring system (or FDET).

7 Information barriers that rely on pre-defined material templates include the Trusted Radiation Inspection System (TRIS) and the Controlled Intrusiveness Verification Technology (CIVET), both developed by US National Laboratories. Information barriers that rely on pre-defined material attributes include the Trusted Attribute Determination System (TRADS) developed by Sandia National Laboratory in the US; the UK-Norway Initiative prototype information barrier (developed jointly by the UK and Norway); and the Attribute Verification by Neutron and Gamma Ray Assay (AVNG) system (developed jointly by the US and Russia).

8 Research and development of 'information barriers' (discussed above) by the US, UK, and Norway has explored the influence of various containers on the detection and characterization of TAIs. See: *Joint U.S.-U.K Report on Technical Cooperation for Arms Control*, National Nuclear Security Administration, Washington, DC: 2015; *The United Kingdom-Norway Initiative: further research into the verification of nuclear warhead dismantlement*, Working Paper 31, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2015/WP.31, New York: 22 April 2015.

9 Hand-held gamma ray spectrometers (such as electrically-cooled germanium crystal systems) may be easy to use in the field, but may not be sufficiently sensitive to produce useful information. Neutron detectors may be able to provide more useful information, but are typically large and cumbersome. Some neutron detectors (such as active well coincidence counters, or AWCCs) require measured objects to be placed within a sample chamber.

10 *IAEA Safeguards: Serving Nuclear Non-Proliferation*, IAEA Department of Safeguards, Vienna, June 2015, p. 16.

11 *IAEA Safeguards: Serving Nuclear Non-Proliferation*, IAEA Department of Safeguards, Vienna, June 2015, p. 74.

12 The risk of such undeclared activities was demonstrated by Iraq prior to 1991, when IAEA inspectors discovered an array of undeclared nuclear activities in contravention of Iraq's safeguards agreement and the NPT.

13 See https://www.iaea.org/safeguards/safeguards-in-practice/information-collection-and-evaluation.

14 That is, when a state has an Additional Protocol to its IAEA safeguards agreement in force, and when the agency has permission from its Board of Governors to do so.

15 E. Kuhn, D. Fischer, M. Ryjinski, *Environmental Sampling for IAEA Safeguards: A Five Year Review*, Vienna: IAEA, 2001.

16 For example, the IAEA was only able to visit the Parchin military complex in Iran to search for indications of undeclared nuclear activities after a protracted period of negotiation with Iran. The procedures that governed this visit were extremely strict. See David Albright, Olli Heinonen, and Serena Kelleher-Vergantini, *IAEA Visit to the Parchin Site*, Institute for Science and International Security, Washington, DC: ISIS, September 2015.

17 James Fuller, 'Going to Zero: Verifying Nuclear Warhead Dismantlement', in Corey Hinderstein (Ed.) *Cultivating confidence: verification, monitoring, and enforcement for a world free of nuclear weapons*, California: Hoover Institution Press, 2010. p. 127 It is worth noting that the first such exploration of nuclear warhead dismantlement verification occurred more than 25 years earlier, with the 1963-1969 US 'Project Cloud Gap'. *Ibid.*

18 Office of Nonproliferation Research and Engineering, 'Technology R&D for Arms Control', *Arms Control and Nonproliferation Technologies*, California: US Department of Energy, National Nuclear Security Administration, Spring 2001.

19 James Fuller, 'Going to Zero: Verifying Nuclear Warhead Dismantlement' in Corey Hinderstein (Ed.) *Cultivating confidence: verification, monitoring, and enforcement for a world free of nuclear weapons*, California: Hoover Institution Press, 2010, p. 158.

20 *IAEA Department of Safeguards Long-Term R&D Plan*, 2012-2023, STR-375, Vienna: IAEA, January 2013.

21 Malte Göttsche, Moritz Kütt, Götz Neuneck and Irmgard Niemeyer, *Advancing Disarmament Verification: A Task for Europe?*, Non-Proliferation Papers, No. 47, EU Non-Proliferation Consortium, October 2015.

# 4. Common Understandings of Verification

The success of any arms control or disarmament treaty rests on shared understandings as to what activities the agreement requires, and what activities it rules out. The treaty text should be well drafted with clear, unambiguous provisions. Ideally, all parties should readily understand the treaty text—and any nuances in interpretation that come about during drafting—at the outset and have a shared understanding about compliance.

However, nuclear disarmament can involve a range of activities—from dismantlement of nuclear weapons, to disposition of fissile material and decommissioning of facilities used for the production of weapons—that will be carried out and verified in different ways. The subject matter covers many complicated scientific and industrial processes, some of which may not be known by NNWS parties to a future nuclear disarmament agreement. For example, detailed weapons knowledge is without exception tightly guarded, and the inadvertent release of such information subject to harsh legal action. Moreover, nuclear arms control and disarmament uses a highly specialised dictionary, where key terms are often difficult to understand.[1] Legal drafters will need to work together with scientists and engineers to formulate precise and unequivocal language. To complicate things further, legal text can be drafted in several authoritative languages. Subtle differences in the meaning of one word in two or more languages can collapse the shared understanding required. Efforts are presently underway to develop a common terminology used in the five nuclear weapons states recognised by the NPT, but more work is required.

These dynamics also apply to formulating text concerning verification. As noted elsewhere in this report, a verification regime should allow parties to reach a compliance determination. The process of making a compliance determination will be frustrated if there is no common understanding as to what compliance means. Similarly, the compliance determination process will be hampered if the parties are not fully cognisant of the tools and procedures available to discriminate between compliance and non-compliance.

Securing a common understanding of commitments and verification provisions places great emphasis on careful and unambiguous wording. For this reason, arms control and disarmament agreements can take months (if not years) to draft and run to hundreds of pages. The New START Treaty—which limits the strategic nuclear arsenals of the US and Russia—runs to a total of 356 pages. These pages include the basic undertakings of the parties, a verification protocol, and three annexes on specific procedures. The verification protocol alone comprises 165 pages of agreed definitions, inspection activities, information exchanges, and consultation procedures.

Parties may also be bound by other agreements that restrict the activities it can commit to. In the NPT, NWS undertake not to transfer nuclear weapons, nor to assist or encourage any NNWS to manufacture or otherwise acquire nuclear weapons. A NWS therefore cannot commit itself to disarming by simply transferring nuclear weapons to any other party. Neither can it commit to verification procedures that would in any way assist or encourage a NNWS to pursue or acquire nuclear weapons. Any multilateral approach to nuclear disarmament verification must be consistent with existing agreements, and this can cause unique challenges.

Verification agreements should represent a common understanding on how verification will be carried out. A nuclear disarmament verification agreement should define a verification regime, taking into account the context of nuclear disarmament (discussed in Section 6.1), the technical environments in which nuclear disarmament might take place (discussed in Section 6.2), and the equipment that might be used to verify nuclear disarmament (discussed in Section 3). As such, exploring the dynamics behind the creation of these common understandings provides an insight into how a multilateral approach to nuclear disarmament verification might be codified in practice.

This section analyses the form and function of nuclear verification agreements, with reference to existing case studies. It will then discuss how hypothetical multilateral verification agreements can be generated and explored to better understand multilateral approaches to nuclear disarmament verification.

## 4.1 Developing common understandings of verification

A common understanding of the tools and procedures to be used to verify compliance with obligations is typically codified through some form of international agreement. This understanding may be included in the text of the agreement, or it may be appended in an annex. In some cases, agreed verification measures may be codified in a separate text, such as a protocol, that refers to, but is not part of, an overarching agreement. Common understandings on agreed verification measures typically include one or more of the following elements:

- An obligation to declare relevant information to other parties (usually baseline data, subsequent periodic updates, and final declarations).
- A description of the mechanisms for compiling and analysing such data and other verification-relevant information.
- A description of allowed procedures and technologies applied to generate assurance regarding the correctness and completeness of declared information. These procedures can include, but are not limited to, remote monitoring (such as provisions for camera surveillance), on-site inspections (whether routine or ad hoc),

and the collection and analysis of physical samples. Sometimes, the agreement states that parties should not interfere with so-called national technical means of verification (for instance space-based monitoring).

- A description of consultation mechanisms: these are sometimes required to resolve technical difficulties or ambiguities or even disagreement over the interpretation of certain treaty provisions.
- An elucidation of voluntary transparency and confidence-building measures designed to provide further information on compliance and clarify ambiguities.
- A description of compliance mechanisms designed to identify and respond to instances of alleged or confirmed non-compliance.

These provisions serve specific functions, and are typically discussed in dedicated sections. The language is often mutually reinforcing. For instance, consultation mechanisms may inform subsequent declarations of relevant information. The declaration of information in turn informs the planning and execution of monitoring, and ultimately the formation of verification conclusions. A verification agreement integrates all the tools and procedures required to verify a treaty into a multi-layered, mutually reinforcing verification system.

## Who decides on verification?

Language on verification measures can be formulated through negotiation between parties, or it can be imposed. States negotiate verification measures during the drafting of an agreement or related protocol but only become subject to its terms when they adhere (ratify or accede) to the instrument. In a multilateral process, this can result in certain states influencing the precise formulation of verification measures to which they do not become a party. The verification measures will, necessarily, be imposed on states that did not join the negotiation process and which adhere to the instrument after its entry into force. Supra-national bodies, such as the United Nations Security Council, can also impose verification measures.

As discussed in Section 6.1, nuclear disarmament may arise out of a number of circumstances. A nuclear-armed state may disarm unilaterally without any overarching disarmament treaty. In this case, the disarming state may offer to voluntarily submit to verification, or it may be forced on it by external factors (such as a legally-binding UN Security Council Resolution).

A voluntary verification offer may be drafted by the verified state, with a verifying party commenting on and potentially agreeing to such an offer. Here, the disarming party would hold most influence over the scope and depth of any resulting verification agreement.

Requests for external verification may also arise in cases of bilateral or multilateral nuclear disarmament. The majority of nuclear arms control agreements between the US and Russia are bilateral, and are verified by the two countries through verification understandings embedded into the overarching treaties. In these cases, both parties are negotiating verification on the principle of reciprocity: both subject to the same restrictions and the same verification procedures.[2]

There are exceptions to this tradition. The Plutonium Management and Disposition Agreement (PMDA) between the US and Russia calls on both parties to dispose of excess military plutonium. In addition to bilateral verification between the US and Russia, the PMDA requires the conclusion of additional verification measures between each party and the IAEA. In contrast to the majority of US-Russia arms control agreements, the PMDA will be verified by a third party, which itself is not subject to the commitments being verified. These two complementary verification schemes (bilateral and multilateral) will take into account differing legal obligations between the US and Russia, and between each party and the IAEA. They will also involve very different tools and procedures, and would be codified in separate agreements. No verification measures with the IAEA have been concluded under the PMDA to date.

Mandatory verification of disarmament will produce a very different dynamic. For example, UN Security Council Resolution 687 (1991) requested the IAEA Director-General to develop a plan to verify the dismantlement of Iraq's nuclear programme and the on-going peaceful nature of any remaining nuclear materials. The IAEA Secretariat drafted the resulting verification plans,[3] which were subsequently approved by the UN Security Council. In this case, the verified state had no input to the verification agreement and was not a party to it beyond its membership of the UN.

## How are common understandings of verification developed?

The pace at which verification arrangements for nuclear disarmament are agreed may vary. As discussed in Section 2, verification aims to build confidence between parties to an agreement, providing assurances that their agreement is being implemented effectively and fairly.

The promise of a future credible verification regime can in some cases be an incentive to states to sign up to an arms control agreement in the first place. However, in other cases parties will need to understand how the agreement is supposed to be verified before they adhere to it. For instance, the 2003 Strategic Offensive Reductions Treaty ('Moscow Treaty' or SORT), which limited the US and Russia to a maximum of 2,200 deployed nuclear warheads, did not contain any specific verification provisions. This fact was sometimes highlighted as one of the main disadvantages with the treaty. However, the Moscow Treaty drew on existing verification procedures agreed in the first Strategic Arms Reduction Treaty (START I)—which remained in force in combination with SORT. In this instance, the implementation of an existing verification arrangement seems to have built sufficient trust between parties to facilitate a new broader arms control treaty.

States may choose to develop a nuclear disarmament agreement and a verification regime simultaneously. This approach allows states parties to update and tailor potential verification approaches in tandem with the evolution of agreed disarmament activities. Similarly, the parties can also restrict or expand the scope of their agreed disarmament activities to accommodate the strengths or weaknesses of acceptable verification measures. The negotiations for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) between 1994 and 1996 in the Conference on Disarmament serve as an example of this mutually reinforcing dynamic. While negotiations over key prohibitions tackled diverging opinions, consensus in parallel negotiations over verification provisions built confidence and drove the process forward.

In rare cases, states will not know, or will only have a rudimentary understanding, of how an agreement will be verified when they sign up to it. Instead, they commit to negotiate verification arrangements at a later date. While this approach may facilitate the negotiation of a broader treaty by postponing difficult negotiations over verification, it may also complicate negotiations by denying parties the assurances that a known verification procedure can provide.[4] The Nuclear Non-Proliferation Treaty (NPT) is a useful example of such an approach. When the Treaty opened for signature in July 1968, it required NNWS to 'accept safeguards, as set forth in an agreement to be negotiated and concluded with the International Atomic Energy Agency [. . .] with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons'. The structure and content of these agreements (as detailed in INFCIRC/153) was not established until June 1972.

## How are common understandings of verification structured?

As discussed above, verification agreements can contain a large array of provisions that must be integrated into a multi-layered, mutually reinforcing verification system. A state party may not be prepared to accept such an agreement unless it is confident that all aspects of this system will operate according to common understandings. For example, states parties may be unwilling to rely on a verification agreement that details only the objectives, principles, and tools for verification. Such an agreement may also have to detail the precise procedures of such verification, including logistical arrangements for inspections; health and safety procedures; liabilities; and reporting and notification requirements.

The level of detail required in any verification agreement depends on the diversity of its parties and of any commitments being verified. If a single state were to undertake a small array of commitments on a well-defined area of activities, the system required to verify these commitments could be fully explained in a single agreement. However, it would be impractical to develop a single agreement that describes the verification of a broad range of commitments, across an array of activities, and among many states parties. Nuclear programmes can exist in a variety of shapes and sizes. If the technical steps for implementing shared commitments differ between nuclear programmes, so too will the procedures needed to verify these steps. Similarly, domestic concerns (such as health and safety, security, information control, and logistical support) will differ between states.

With this in mind, the diverse range of provisions that describe an acceptable verification system for any one set of commitments may be spread across a number of linked agreements. The broad principles, applying equally to all parties, may be detailed in one overarching document, signed by all. The subsequent technical details of verification may be set out in subsidiary agreements between individual states and a verifying party.[5] The precise content of these subsidiary agreements, as well as the procedures governing their negotiation and distribution, may vary between parties.

Verification agreements between NNWS and the IAEA are an illustrative example. These agreements are all based on a single document (INFCIRC/153) that defines the structure and content of verification agreements between the IAEA and NNWS. This document in turn was created by the organisation's secretariat with the input of technical experts from its member states, and was subsequently approved by a forty-eight-member safeguards committee. In other words, not all states applying safeguards—perhaps not even a majority— have been involved in formulating the rules themselves.

Individual safeguards agreements between the IAEA and NNWS mirror this document, but refer to 'subsidiary arrangements' to be made between the state and the IAEA detailing how the safeguards agreement will be implemented in a specific case. These subsidiary arrangements consist of a general part (detailing the substance and procedures of information exchanges between the state and the IAEA), and separate attachments for each nuclear facility in the state. These arrangements are held in confidence, and can be amended or supplemented without amending the safeguards agreement itself.

## 4.2 Creating verification agreements

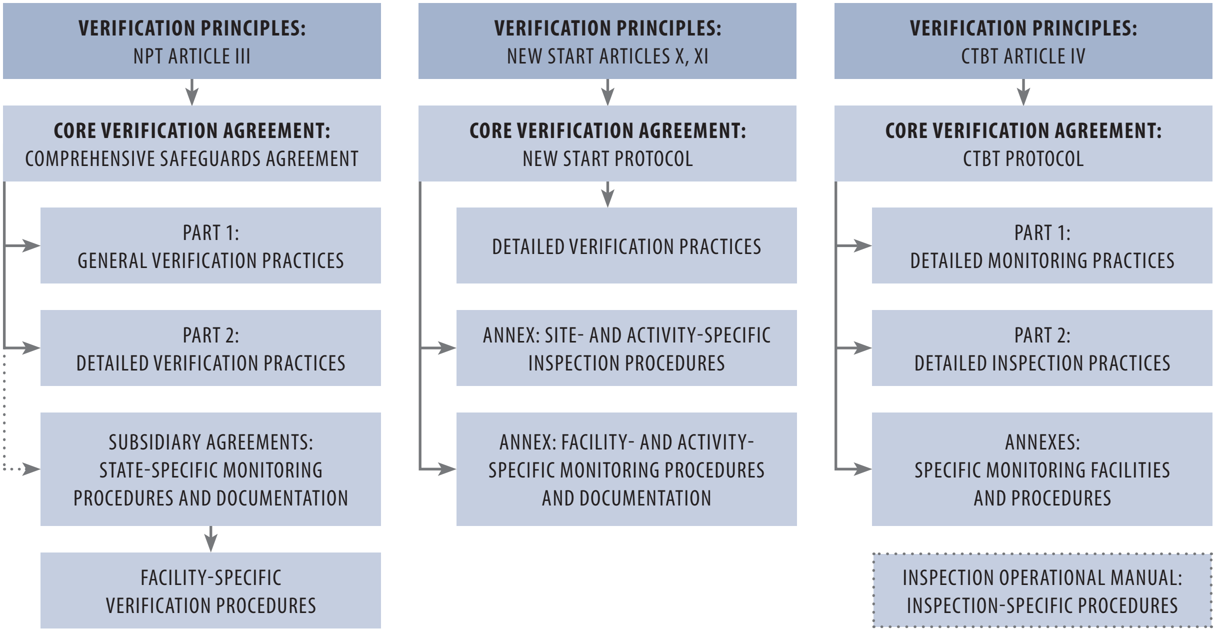
Verification agreements, as described above, are the product of a combination of factors. Their scope and contents are determined by a common understanding of certain activities that are required or are prohibited (as described in a treaty or other agreement). The activities they describe are shaped by the characteristics of states being verified, and the technical steps they have to take to deliver their shared commitments. Many actors can be involved in their development, some of which may not even be subject to the commitments being verified. Existing verification agreements—such as those integrated into the PMDA, the CTBT, and the NPT—are therefore unique products of the political and technical circumstances of their development.

This does not mean that verification agreements can only be explored within the context of an existing treaty, and through the technical and political circumstances that brought such a treaty into existence. As described above, the promise of a credible verification regime can also encourage states to consider codifying mutually desirable actions or restrictions into a treaty. Just as technical trials can explore the credibility of new verification tools, the development of hypothetical verification agreements can explore the credibility of the procedures and practices that would apply these tools to new verification challenges. Hypothetical verification agreements can be developed by creating a generic structure from existing verification agreements, identifying specific provisions that might be required to verify a set of predefined commitments, and populating these provisions with draft language.

## A generic structure for verification agreements

As discussed above, the provisions of any verification agreement—and the manner in which this agreement is created—vary considerably from case to case. However, it is possible to identify a common structure for these agreements that provides a useful framework through which to consider hypothetical verification agreements.

**Figure 4.1** Structure of different existing verification agreements



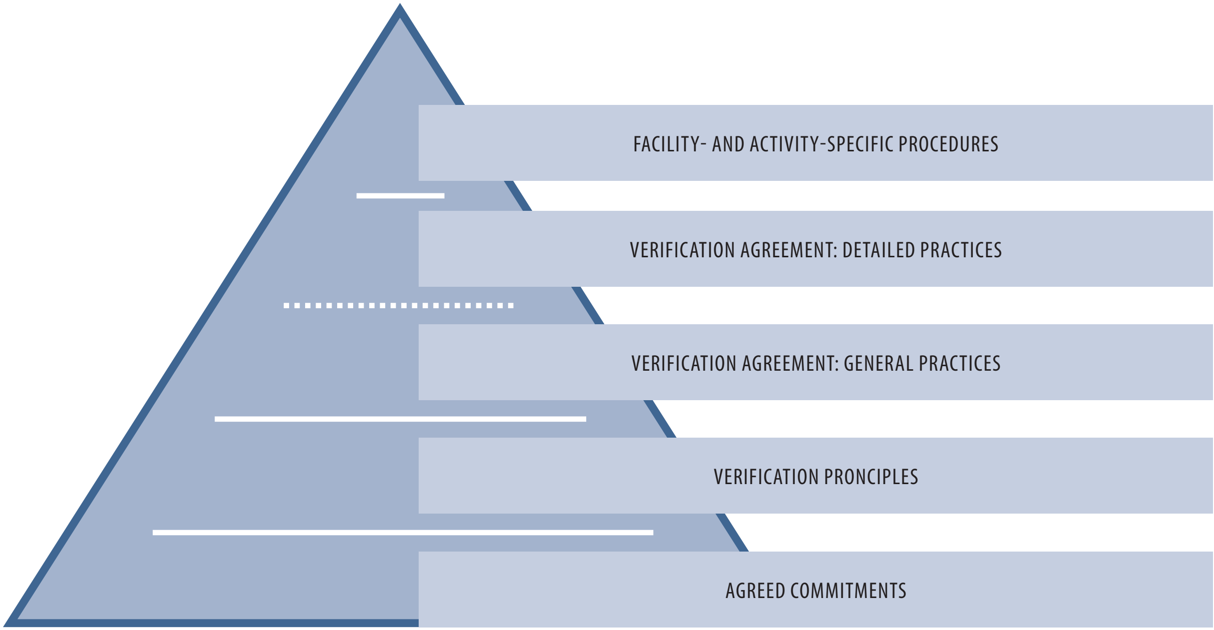
IAEA Safeguards Agreements under the NPT, the New START Treaty between the US and Russia, and the CTBT provide useful examples for this.

These three examples demonstrate a common structure to verification agreements. First, the core principles of verification are established. This gives a general impression of the aims and objectives of verification, and bounds the scope of the type of activities that verification might involve. These principles are established alongside the commitments to be verified.

Second, a core verification agreement develops these principles into a range of agreed verification practices. These practices typically include the provision of information by a verified state to a verifier, other monitoring techniques available to a verifier, and the remote or on-site tools available to verify information. This core verification agreement can establish the general outline of these practices before providing details, or it can establish the details directly.

Finally, specific procedures associated with the provision and verification of information are established in annexes or separate documents. These provide the most detailed description of the practical implementation of an agreed verification system, and typically refer to specific facilities or activities of concern to verification. This generic structure can be outlined as follows:

**Figure 4.2** A generic structure for verification agreements



## Identifying verification provisions

The generic structure described above provides a stepwise process for identifying and coordinating the provisions that could ultimately define a verification system. The first step is to consider what commitments will be subject to verification. Under nuclear disarmament agreements, verifiable commitments might range from the dismantlement of nuclear warhead stockpiles through to the decommissioning of fissile material production facilities.

A second step involves outlining the broad objectives of verification in this particular scenario, as well as the tools that might be available to achieve these goals. In principle, verification may be limited only to facilities and activities that have been declared by a state party as relevant to the implementation of agreed commitments. Consequently, if the verification goals are limited only to the confirmation of declared information, states parties may also rule out the use of broad surveillance techniques (such as wide-area environmental sampling or satellite reconnaissance). In contrast, states parties may agree that verification should seek to confirm declared information in addition to the *completeness* of those declarations. In this case, the techniques allowed may be more diverse.

A third step would take the general principles and tools established above to develop a list of practices which together would achieve the agreement's objectives. An outline of common verification practices is given

**Table 4.1** Common verification practices

| | | |
|---|---|---|
| **Provision of information**<br>● Types of declaration (initial, periodic, ad hoc)<br>● Contents of declarations<br>● Record of declarations<br>● Submission of declarations<br>● Receipt of declarations<br>● Requests for additional information | **Handling of information**<br>● Use of open-source information<br>● Use of third-party information<br>● Confidentiality procedures<br>● Application of declarations<br>● Application of other information | **Inspections**<br>● Types of inspection (regular, ad hoc, challenge)<br>● Objectives of inspections<br>● Planning of inspections<br>● Notification of inspections<br>● Implementation of inspections<br>● Managed access procedures |
| **Reporting requirements**<br>● Inspection reports<br>● Declaration reports<br>● Confidentiality reports<br>● Verification conclusions<br>● Dispute resolution | **Equipment controls**<br>● Agreed inspection equipment<br>● Agreed monitoring equipment<br>● Equipment development<br>● Equipment certification<br>● Equipment deployment | **Regulatory concerns**<br>● Health and safety regulations<br>● Security requirements<br>● Verifier's liabilities<br>● Third party liabilities |
| **Finances**<br>● Inspection funding<br>● Declaration funding<br>● Equipment funding | **Definitions** | **Entry-into-force and amendments** |

in Table 4.1, but it is worthwhile remembering that this list would be subject to the top-level commitments and verification principles described above.

A comprehensive list of verification provisions provides a framework in which specific language can be developed. The scope of this language depends on the uniformity of commitments undertaken by states parties. As noted above, an important distinction must be drawn between language describing general verification activities and language describing verification activities that are unique or specific to certain facilities. Language describing such specific activities can only be developed with reference to known and well-characterised technical requirements (such as unique warhead dismantlement procedures, or technical facility specifications).

## Developing draft language

Existing verification agreements provide a useful repository of credible language that can be adapted to hypothetical cases. Inspection procedures for a variety of facilities or sites are described within agreements such as the CTBT, the Chemical Weapons Convention (CWC), the New START agreement, and IAEA safeguards. Furthermore, these agreements contain a number of standard definitions of items, activities, and concepts that are relevant to verification. Many of these definitions have been collated and built on in the P5 Glossary of Nuclear Terms, presented to the 2015 Review Conference of the NPT.

The Trilateral Initiative, which brought the US, Russia, and the IAEA together to explore techniques for verifying the transfer of military plutonium to civilian uses, drew on existing agreements to develop a model verification agreement for hypothetical disarmament commitments. Drawing on the language and structure used within the IAEA's safeguards system, the three parties were able to develop the majority of a draft Model Verification Agreement for the Trilateral Initiative. The Trilateral Initiative sought to develop 'subsidiary arrangements' to this agreement that would give specific procedures for the practical application of agreed verification techniques, but was unsuccessful in achieving this aim. An alternative variation of this model agreement has been published for debate and discussion among governmental and non-governmental organisations.[6]

## Section 4 endnotes

1 The difference between US and Russian interpretations of 'nuclear warhead' was noted and explored as early as 1998. See: Anna Hadley, *Just What Exactly is a Warhead?: An Analysis of Russian/English Translations and Definitions*, Sandia Report, Sandia National Laboratory, June 1998.

2 The principle of reciprocity also applied in the negotiation of verification mechanisms for multilateral treaties such as the Comprehensive Nuclear Test-Ban Treaty (CTBT) and the Chemical Weapons Convention (CWC)

3 *Note by the Secretary-General, Plan for future ongoing monitoring and verification of Iraq's compliance with paragraph 12 of Part C of Security Council Resolution 687 (1991) and with the requirements of paragraphs 3 and 5 of Resolution 707 (1991)*, S/22872/Rev.1, 20 September 1991.

4 Delaying the negotiation of verification arrangements until after an agreement is finalized also risks them being postponed indefinitely.

5 The broad verification principles outlined in an overarching document may require these technical verification details to be negotiated and implemented by a separate state or intergovernmental organisation (such as the IAEA), which is not party to the overarching document.

6 Thomas E. Shea and Laura Rockwood, *IAEA Verification of Fissile Material in Support of Nuclear Disarmament*, Cambridge, Mass.: The Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, May 2015.

# 5. Exploring Verification through Simulations

Verification describes a set of processes or procedures that allow actors to monitor and assess the implementation of an agreement or the truth of a statement. The requirements for these verification processes vary depending on the context. In the case of nuclear disarmament verification, the requirements will depend on the political relations between actors and the circumstances that brought about nuclear disarmament (see Section 6.1). The requirements of nuclear disarmament verification will also depend on the scale and complexity of agreed nuclear disarmament activities (see Section 6.2), the tools available to monitor these activities (see Section 3), and the agreed legal structures for implementing verification (see Section 4).

Any exploration of nuclear disarmament verification that ignores these contextual factors will provide little information as to how disarmament verification could or should be achieved in the real world. The current political, technical and legal context of nuclear disarmament—reflected in the domestic and international politics surrounding nuclear weapons, the size and composition of nuclear weapon programmes, and the domestic and international legal structures that govern states' behaviour—can be incorporated into disarmament verification 'simulations' that explore the verification of existing or hypothetical disarmament agreements. For example, a simulation could bring together nuclear-armed states to explore which equipment and monitoring processes they might require or allow within an existing nuclear facility to verify a potential Fissile Material Cut-off Treaty.

Disarmament verification simulations that incorporate a high degree of realism—reflecting the current political, technical, and legal context with a high degree of accuracy—can generate powerful insights into contemporary disarmament issues. Participants can identify and explore the challenges and opportunities presented by verified disarmament activities before undertaking them in the real world. Realistic verification simulations—such as those that exercise existing arms control, disarmament, and non-proliferation agreements—will always play a central role in strengthening confidence between states.

However, the more realistic a simulation is, the harder it becomes to avoid the challenges that confront nuclear disarmament in the real world. Not all stakeholders will be willing to participate in a realistic simulation of nuclear disarmament activities that are sensitive and subject to broader geopolitical concerns. Those that are prepared to explore these activities may disagree on what the main issues are, and how they should be addressed through an exercise. Exploring the application of experimental monitoring equipment to real (and potentially active) nuclear facilities can be dangerous, highly sensitive, and possibly proliferative. Developing and implementing verification exercises for existing disarmament-related initiatives is politically fraught, time-consuming, complex, expensive, and in some cases, hazardous.[1] Taking a step back from the real world by introducing hypothetical disarmament verification challenges can avoid these problems without ignoring them entirely; building confidence in multilateral disarmament verification and facilitating its exploration in real-world scenarios.

This section discusses how hypothetical verification simulations—incorporating hypothetical nuclear weapon programmes and disarmament scenarios—can explore the multilateral verification of nuclear disarmament. The objectives and requirements of such simulations are discussed here, and methodologies for exploring technical, legal, and political issues raised by multilateral verification of disarmament are discussed in the following sections.

## 5.1 Introducing verification simulations

The purpose of verification simulations is to allow a group of individuals to discuss, negotiate, and test individual or integrated procedures and equipment for verifying hypothetical disarmament environments. Such simulations are commonplace in certain arms control, disarmament and non-proliferation regimes.[2] They enable participants to practice activities in a non-classified, apolitical, repeatable and focussed manner and help to build confidence that verification is achievable. Activities that might be hazardous, costly, security-sensitive, time- and effort-consuming or otherwise prohibited can be replicated in a hypothetical environment, where these challenges can be examined from a safe distance. Replicating real disarmament activities—and the real technical, legal, and political dynamics surrounding them—in a more hypothetical setting can identify the strengths and weaknesses of disarmament verification while avoiding the possible dire consequences of getting a real-life activity wrong.

Hypothetical disarmament environments can also be created that focus on individual aspects of a verification challenge, rather than having to tackle all technical, political, and legal issues at once. A simulation can be created to test legal principles for disarmament verification, such as the process for defining and negotiating a verification system within the bounds of domestic and international law. Simulations can also be created to explore technical issues, such as the equipment and processes involved in verifying disarmament. Similarly, they can explore policy concerns, including those relating to legal and technical aspects, to reveal current attitudes toward verification and to inform an on-going disarmament verification research agenda.

# Principles of verification simulations

## Simulation objectives

Verification simulations must be designed and implemented to ensure they make a valuable contribution to disarmament verification efforts. First, a verification simulation must have a clear and well-defined objective, relating to what the simulation should try to achieve in the real world. Box 5.1 provides a list of examples of possible objectives.

While the objectives of a simulation can range from the ambitious to the restrained, it is vital that any objectives are clearly described and compatible with each other. These objectives ultimately guide the design and implementation of a simulation, including the generation of hypothetical disarmament scenarios, the modelling of hypothetical nuclear weapon programmes, the selection of simulation participants, and the actions of these participants.

## Simulation tasks

The objectives of a simulation should dictate the tasks that should be carried out within a simulation. If the simulation aims to train and build general capacity among participants, it should be designed in a way that focuses activities on a broad range of issues that participants are currently unfamiliar with and allow participants to explore these issues to a desirable depth. A simulation that tasked participants to develop detailed verification procedures for a single disarmament activity, drawing from a limited range of equipment, may not achieve this objective. The hypothetical simulation environment should take these tasks into account, and these tasks should be clear and understandable to the participants.

### **Box 5.1** Indicative list of simulation objectives

A verification simulation could aim to:

1. Develop an outline verification agreement that could become a foundation for a range of future nuclear disarmament verification activities;
2. Develop a detailed verification agreement, including precise monitoring procedures and compliance processes, that could be applied to a specific disarmament activity;
3. Explore one specific aspect of nuclear disarmament verification (such as the trade-off between transparency and information protection, or the influence of domestic political factors) for a range of disarmament scenarios;
4. Explore the application of selected monitoring equipment for the verification of certain disarmament activities;
5. Test the verifiability of existing disarmament agreements, or hypothetical agreements developed through other verification simulations;
6. Train and build capability among the participants, and to pass on knowledge and expertise to emerging actors in the field;
7. Encourage engagement between key disarmament verification stakeholders whose interactions over more sensitive real-world topics might be limited by practical or political constraints.

### Simulation outputs

The simulation objectives should also inform the intended outputs of the simulation, which should be established at the outset. Depending on the objectives, a simulation could aim to produce draft or outline verification agreements for hypothetical disarmament scenarios that can serve as a focus point for on-going debates about various routes toward nuclear disarmament. A verification simulation could also produce practical research reports or presentations that can guide the research and development of future verification technologies, or identify areas ripe for further investigation. Those running a simulation must be able to draw on observational tools such as questionnaires, discussion groups, and recording techniques to facilitate these outputs without interfering or interrupting the simulation itself.

## Key components of a verification simulation

The precise construction of a verification simulation—from the scenario it explores through to the specific tasks for participants—depends on the objectives mentioned above. However, it is possible to discuss some general requirements for a successful simulation that would be common to any given objective.

### Participants

Simulations must be able to draw on the most appropriate participants to fulfil its objectives. Participants that may be benefit from a capacity-building and training simulation may not be appropriate for a simulation aiming to develop and test a detailed set of verification procedures. Participants must also be assigned to suitable roles within a simulation. While it may be educational for a political expert to be assigned a technical role within a simulation, this assignment may not facilitate other potential objectives. Typical roles for simulation participants include:

- Players, who adopt and explore the perspective of either a verifying or a verified party;
- Observers, who record (but do not influence) the passage of a simulation to identify key lessons learnt and to facilitate the production of simulation outputs;
- Controllers, who develop a simulation and guide players and observers through their tasks, through interactions inside or outside the simulated environment.

### Authenticity

A simulation cannot generate insights into a nuclear disarmament verification scenario unless players carry out their tasks according to that simulated scenario. While players may have to rely on technical knowledge gained from the real world to complete their simulation tasks, political preconceptions or prejudices may influence their actions, and therefore the results of the simulation.

A simulation must create a detailed and credible environment from which players can complete their tasks without recourse to preconceptions or prejudices. This environment needs to introduce players not only to their role within the simulation, but also to the roles of other participants, and their relations with each other. Developing hypothetical scenarios and weapon complexes that draw on (but do not necessarily reflect) recognisable aspects of real-world counterparts can make it easier for players to adjust to a simulated environment. The exercise resources must also equip players with the required level of knowledge regarding the sites, materials, and processes involved in the hypothetical disarmament activities, including the incentives and restrictions related to their verification.[3]

## Materials

In order for players to have sufficient knowledge of the simulation features and characteristics noted above, the fictional world must be described by its creators in a clear and unambiguous way, so that it can be held in the minds of players in role-play simulations, with the help of maps, diagrams and data as reference material. In addition, planners need to provide appropriate resources, including introductory or background materials describing the simulation environment; in-play documentation and mock objects of verification such as nuclear material or warheads; and controller materials such as agendas, observation schemes, and injects that introduce new information or tasks to a simulation.

## Medium

Finally, a simulation must take place in a medium that effectively establishes an authentic environment, through which players can interact effectively with each other, their tasks, and the materials provided to them to achieve these tasks. Simulation mediums can include table-top exercises, model facilities, virtual reality environments, modified general-use facilities, and even real nuclear facilities. Selecting a medium involves balancing practical considerations (such as timescale and expense) against the desire to achieve the greatest authenticity in a manner that best achieves a simulation's objectives. For instance, table-top simulations can draw a number of participants together quickly and flexibly. However, they rely on highly detailed and engaging materials to establish an authentic environment. Similarly, mock-up facilities can strengthen the authenticity of a simulation, but can also be time-consuming and expensive to generate.

## Directing a simulation: some examples

Developing a verification simulation involves setting a clear objective, translating this objective into simulation tasks, creating a detailed and credible simulation environment, and then placing players within this environment to complete their tasks. Executing a verification simulation involves directing and controlling these players toward their tasks, and observing how they approach them, without compromising the simulation's authenticity.

For example, a table-top simulation could bring together a group of players (who have been briefed on their roles and the simulation environment) to negotiate inspector access rights to a particular facility. These negotiations could have a pre-determined deadline that all players must aim toward. To achieve these deadlines, players may be required to remain within the simulation environment for a large amount of time—leaving the simulation only for meal breaks. Break-out sessions, comfort breaks, and even accommodation can be included in the simulation environment.

While this approach may maximise the authenticity of the simulation for players, it requires careful planning by the designers to keep the simulation on track. A control team may have to suspend the simulation to direct players toward or away from certain issues to help them fulfil their tasks. An alternative approach would break the simulation into individual sessions, between which players, observers, and controllers could reflectively discuss issues raised, and prepare for approaching sessions. These 'working groups' could focus on technical, political, or legal issues, and even begin meeting before being introduced to the simulation itself, to prepare some initial positions between players.

The duration of these sessions could be adjusted to match the number of tasks, the capabilities of the participants, and the ultimate objectives of the simulation. For instance, if a simulation aimed only to build knowledge and capacity among players, a controller could talk players through a simulated environment, their respective tasks, and associated issues. Players can then discuss their tasks outside the simulated environment, without behaving strictly according to their assigned roles.

However a verification simulation is directed, controllers must bear two important issues in mind. First, a simulation must be directed in a way that produces the desired outputs. If a simulation aimed to produce a draft set of agreed inspector access provisions for a certain facility, directing players through a 'walk-through, talk-through' simulation, with little negotiation within the simulated environment may not generate procedures that would actually be agreeable within the chosen scenario. Producing this output may require players to spend a large amount of time within the simulated environment.

Second, a simulation must be directed in a way that meets the desired objectives. If a simulation aimed to explore all the issues that might arise from the multilateral verification of a certain activity, controllers should avoid directing players toward certain issues and away from others to fulfil a long list of prescriptive tasks.

While this approach may make it easier to carry out a simulation, it would stifle the exploration of unexpected issues. The more scripted and controlled these exercises are (regardless of whatever medium is used) the less will be learned. In an extreme case, players following a tight script will simply go through the motions that were planned for them, nothing new or unpredicted will emerge from the simulation and nothing new will be learned. If the simulation aimed only to inform participants, then this approach may be suitable. Otherwise, precise and prescriptive direction can hinder, rather than help, a simulation.

## 5.2 Exploring monitoring equipment and technologies

Verification relies on the ability to monitor behaviour to identify instances of compliance or non-compliance with an agreement or declaration. The nature of most disarmament or arms control activities is such that monitoring is normally carried out through specialised equipment (as discussed in Section 3).

- Monitoring equipment is often used to:
- Identify and characterise items or materials that are relevant to verification;
- Characterise processes that are relevant to verification;
- Identify any changes to these items or processes;
- Detect any hidden items or processes that are relevant to verification.

Monitoring equipment can provide more accurate and diverse monitoring information, and can do so more reliably from varying locations, than human observation alone. However, it is rarely perfect. The accuracy of equipment, its operability and suitability for various environments, as well as the manner in which it is applied limit the contribution monitoring equipment can make to a verification judgement. As discussed in Section 3, the specific characteristics of disarmament activities dictate the technical requirements and restrictions involved in the collection of monitoring information and the judgement of compliance or non-compliance.

All nuclear-armed states are able to examine their own nuclear weapon programmes unilaterally to explore technical issues associated with potential arms control and disarmament verification missions. Some states—particularly the US and UK—have explored the technical requirements and restrictions presented by some nuclear disarmament or arms control activities through a number of highly realistic simulations. The US and Russia have also conducted bilateral exercises on real nuclear weapons to explore the application of monitoring equipment,[4] as the UK has also done with the US.[5]

Collaborative exercises will continue to play a vital role in exploring the technical issues surrounding nuclear disarmament verification. However, designing and executing these exercises is a time- and resource-consuming enterprise. As mentioned in Section 5.1, real nuclear items and facilities present real safety and information security risks, which are exacerbated in a bilateral or multilateral context. While the UK-US collaboration is facilitated by a unique nuclear weapon cooperation agreement dating back to 1958,[6] the future of other collaborative exercises depends on a sustained level of trust, patience, and commitment between participants.

Simulations can play a complementary role in exploring the technical issues behind nuclear disarmament verification. The facilities involved in nuclear disarmament can be re-created virtually; mirroring the features of real facilities that are relevant to verification and addressing the safety or security risks they present from a safe perspective. The form, composition, location, and status of nuclear materials involved in creating and disarming nuclear weapon programmes can be modelled as discussed in Section 6.2, to provide an approximate and unclassified picture of disarmament activities. Simulated disarmament environments can be created and repurposed according to a range of different disarmament scenarios and nuclear fuel cycle models—from the disarmament of states with small and basic nuclear weapon programmes to states with larger and more sophisticated nuclear weapon capabilities. This section discusses a range of technical issues that verification simulations might explore, and describes the objectives and requirements of potential future simulations.

## Technical challenges to nuclear disarmament verification

Nuclear material detection and characterisations technologies are never 100 per cent accurate. An insignificant uncertainty in one measurement can become significant if repeated over time. A measured discrepancy of ten grams in a single two kilogram container of enriched uranium may seem unimportant, but the same discrepancy in 100 two kilogram containers may not. Small measurement uncertainties can propagate through a complex monitoring system to become a large impediment to discriminating between compliance and non-compliance. Both verifying and verified parties must understand the unavoidable uncertainties introduced by monitoring equipment, and have confidence that these uncertainties will not obstruct or pervert a verification judgement.

Equipment that can provide a suitable level of accuracy in one situation may not be able to provide the same assurance in another situation. As discussed in Section 3, nuclear disarmament activities can take place in a number of awkward, sensitive, and hazardous locations. The nature of these locations, or the activities taking place within, can make the application of established technologies untenable. But novel technologies that could be more appropriate may be poorly understood, prohibitively expensive, and distrusted by either the verifier or the verified, or both.

A technology is only as useful as the manner in which it is applied. If a verifying party is not confident that monitoring equipment is deployed in the right places and in the right quantities, the information collected by that equipment would make little constructive contribution to verification. The same problem arises if a verifying party is not confident that they can collect the information generated from such technologies without it being tampered with or spoofed. A verifying party must be able to 'authenticate' the information collected by monitoring equipment, just as a verified party will need to certify that such equipment operates only according to their requirements for safety and security. In some scenarios—such as those where a state has agreed to destroy or decommission nuclear weapon manufacturing facilities —these requirements will be extremely stringent.

These issues combine to describe the role that technology plays in facilitating judgements of compliance or non-compliance with an agreement. This role is typically very significant, but technological imperfections prevent it from becoming the sole determinant of verification judgements. The manner in which a verifying party deals with uncertain or imperfect monitoring information draws on the political relations between verifying and verified parties (such as their respective levels of trust, as described in Section 6.1), and the mechanisms built into any legal disarmament or verification agreement between the parties to resolve uncertain or imperfect information (such as consultations and follow-up inspections).

## A case study: the UK-Norway Initiative

The UK-Norway Initiative (UKNI) is 'an ongoing collaboration between a non-nuclear-weapon state and a nuclear-weapon state which seeks to investigate technical and procedural challenges associated with a possible future nuclear disarmament verification regime.'[7] One of the principle objectives of the initiative is to create scenarios in which the participants can explore issues relating to nuclear arms control without the risk of transferring information that might violate their non-proliferation commitments under the NPT.

To achieve the initiative's research objectives, the participants began two separate projects: one developing 'information barrier' technologies,[8] and the other exploring 'managed access' concepts for the verification of nuclear warhead dismantlement. The 'managed access' project has developed and executed a number of simulations, through which the initiative explores approaches to managed access and tests the technologies developed by the 'information barrier' project. These simulations aimed to:

- Test technologies and procedures for the verified dismantlement of a hypothetical nuclear warhead within a hypothetical nuclear facility;
- Gain an understanding of the factors that influence what verification practices are acceptable to either the verifying or verified parties;

- Discuss the level of confidence gained by both verifying and verified parties through verification practices; and
- Consider the level of cooperation that both parties would have to accept for such verification to be successful.

The first simulation was held in 2008, and involved a four-day familiarisation visit to a hypothetical nuclear facility. Players adopting the role of a verified party demonstrated a hypothetical disarmament activity (using mock-up items) to players adopting the role of a verifying party, who were required to familiarise themselves with the activity and reach agreement with their hosts on the broad verification tools and techniques that might be applied. This involved a mixture of simulated negotiations and live action role-playing, with escorted visits to the mocked-up facilities where the disarmament activity would take place.

The broad verification tools and techniques agreed in 2008 were then explored a year later during a one-week monitoring simulation. Players adopting the role of a verifying party were tasked with implementing agreed verification procedures on the dismantlement of a mock nuclear weapon, using real verification equipment, including two prototype information barriers.

A third simulation repeated the familiarisation visit conducted in 2008, but drew on a different notional disarmament activity and a different mocked-up facility. The simulation also sought to introduce safety concerns regarding the notional disarmament activity. Players representing the verifying party were tasked with developing an understanding of the disarmament activity, including the processes, tools, and facilities involved, and to consider potential verification procedures. The execution of these three simulations depended on the following resources:

- *Prototype equipment for testing within simulated scenarios*

  Two prototype information barriers were developed by the UK and Norway to test within simulations.

- *A detailed and credible disarmament scenario that enabled players to act according to their respective roles*

  This included background briefings on the political, economic, and security histories of the verifying and verified parties, exchanges of letters, and a briefing on the verified party's nuclear establishment. It did not include a full copy of the legal agreements formalising the disarmament scenario.

- *A detailed and credible disarmament activity*

  Players adopting the role of the verified party required a detailed understanding of the dismantlement process they would undertake, and the political, security, and safety factors that would influence their approach to agreeing verification provisions. This dismantlement process was developed on paper by simulation participants prior to the simulation, and demonstrated to players representing the verifying party in practice through the mock-up resources below.

- *Mock-up items and facilities associated with this disarmament activity*

  The facilities associated with this disarmament activity were developed from a generic facility model that drew on basic features of a nuclear weapon facility. Real facilities in the UK and Norway were then modified to resemble these mock-up features.[9] The nuclear weapon at the heart of the disarmament activity was represented by a Cobalt-60 source.

## Technical verification simulations: objectives, tasks, and requirements

The UK-Norway Initiative provides useful examples of the technical goals verification simulations might aim to achieve. Simulations within the UK-Norway Initiative aimed to explore 'managed access' procedures for monitoring the dismantlement of a nuclear warhead, build an understanding of the pressures that determine the acceptable boundaries of such procedures, and to test prototype equipment within these procedures. Verification simulations can build on the outputs of the UK-Norway Initiative, but they can also explore a range of different technical issues associated with nuclear disarmament verification.

As discussed above and in Section 3, verification typically relies on monitoring equipment to inform judgements of compliance or non-compliance. Verification simulations can explore the capabilities of existing equipment, and the requirements for future equipment, by focussing on two separate but complementary objectives.

### Exploring the application of existing technologies

First, a verification simulation could aim to build an understanding of how an existing example of verification equipment could be applied to a range of nuclear disarmament activities. For instance, verification simulations could aim to understand how 'information barrier' concepts developed for the monitoring of nuclear weapons and nuclear weapon components could be applied to other nuclear and non-nuclear items or processes that might be involved in nuclear disarmament. Such a simulation could task players to consider a selected range of simulated disarmament activities—such as the disposition of explosive lenses removed from dismantled weapons, or the disablement of weapon component fabrication plants—and discuss how information barrier technologies could be used to verify these activities. Players in such a simulation would need to draw on a shared and detailed understanding of the materials and processes involved in these activities, that could be generated through the modelling techniques discussed in Section 6.2.

Players would also need to draw on knowledge of the capabilities and weaknesses of current information barrier technologies and monitoring equipment. If players are tasked to approach this topic from the perspective of a verified or verifying party, they must also be equipped with sufficient background information regarding the political, legal, and security drivers behind each to adopt such a perspective. Such a simulation could produce a jointly-authored research report to introduce new verification approaches to policy-makers and illuminate new research avenues for experts in the technologies being explored. Such a simulation could also produce a set of principles governing the use of information barriers from the perspective of both verifying and verified parties, to be considered during any discussion of nuclear disarmament verification in the real world.

## Exploring the requirements for monitoring technologies

Second, a verification simulation could aim to build an understanding of precisely what equipment should be applied to verify a single disarmament activity. In contrast to the simulation objective described above, this would focus a simulation onto a single disarmament activity, rather than a single type of equipment. For example, a verification simulation could generate a hypothetical scenario in which a state has decided to undertake a specific disarmament activity—such as the down-blending of excess fissile material components—and invite a multilateral party to verify this activity.

Players within this simulation could be tasked with adopting the perspectives of either the verifying or verified parties to discuss and reach broad agreement on verification practices to be applied. If such a simulation aimed to explore the application of monitoring equipment in greater detail, it could task players to familiarise themselves with the disarmament activity (as was achieved by the UK-Norway Initiative above), and produce more detailed proposals for the application of this equipment.

If the disarmament activity can be simulated to a sufficient level of detail, players may also be tasked with exploring the technical accuracy and operational constraints of agreed equipment when applied to this activity. For example, modelling techniques discussed in Section 6.2 could produce information on the precise quantities, chemical forms, and physical morphologies of the materials passing into and out of a disarmament activity. A simulation could use this information to produce a disarmament 'declaration' that outlines the parameters of what would be considered compliance or non-compliance with the chosen activity. Comparing the technical capabilities of a proposed monitoring system against this declaration could highlight how measurement inaccuracies or gaps in monitoring might affect the ability to draw conclusions of compliance or non-compliance.

## Requirements

The simulation approaches described above place an emphasis on detailed and credible technical modelling to allow players to understand the type of monitoring information required, the accuracy to which such information needs to be collected, and the operational constraints regarding how such information can be collected.

Modelling must describe not only the materials involved in a hypothetical disarmament activity—including the quantities, chemical forms, and physical morphologies. It must also aim to describe the processes, facilities, and equipment involved in processing these materials.[10] The level of detail given by this modelling must match the tasks that are set to players. If players are asked only to explore general proposals for a verification monitoring system for a chosen disarmament activity, the modelling behind this activity may not have to provide precise information on the bulk quantities of materials involved, or the precise parameters of the procedures involved.

This emphasis on technical modelling does not make other aspects of the simulation environment entirely unnecessary. If these simulations also aim to understand how less technical factors—such as political relationships—influence the role of monitoring equipment in verifying disarmament, this modelling must also be supported by similarly credible backstories.

Finally, participants must also understand precisely what activities have been agreed to before they can explore how compliance or non-compliance with an agreement should be verified. This shared understanding is typically codified in legal texts, such as treaties and agreements. Technical simulations can draw on existing agreements or treaties in this regard – such as drafts for a Fissile Material Cutoff Treaty or the model agreement for IAEA verification of fissile material in relation to nuclear disarmament.[11] Technical simulations can also draw on agreements or treaties produced by legal approaches to verification simulations, as discussed in Section 4.

## 5.3 Exploring common understandings and verification agreements

Verifying nuclear disarmament is a complex endeavour. Any system that aims to achieve this must take into account the political circumstances that brought disarmament about, the required technical tasks, the verification equipment available, and the issues that affect how such equipment can be applied.

While any of these issues are worthy of close examination in isolation, they are not independent of one another. The political circumstances of disarmament will influence the technical approaches used to verify it,[12] and vice-versa. Exploring the negotiation and implementation of verification agreements can provide a holistic perspective of multilateral approaches to nuclear disarmament verification. As discussed in Section 4, verification agreements represent a shared understanding between parties of how the implementation of commitments will be verified.

Securing common understanding of shared commitments and verification procedures requires carefully drafted and unambiguous wording. This is particularly the case for multilateral approaches to disarmament verification, where states parties to a verification agreement may have varying levels of technical expertise, and may not share the same language. Negotiating multilateral agreements to verify nuclear disarmament will be challenging, and exploring the legal factors involved in depth can make an important contribution to building credible and robust multilateral verification mechanisms. The promise of a credible verification regime can also be an incentive for states to sign up to a disarmament agreement.

This section explains how verification simulations can explore the negotiation and implementation of legal agreements for the verification of nuclear disarmament activities. It provides an overview of the issues that can be explored through such simulations, before discussing how such simulations can be developed.

## The challenges facing common understandings of nuclear disarmament verification

Verification aims to generate assessments of parties' compliance or non-compliance with an agreement. The ability to achieve this rests not only on a shared understanding of what precisely constitutes compliance or non-compliance, but also on a shared understanding of the tools and procedures available to discriminate between the two. There are a number of hurdles to the creation and negotiation of such a shared understanding.

### Shared definitions

Translating definitions of key terms from one language into other languages can be challenging. Even in recent years, dialogue between the US and China on nuclear matters has stumbled over competing definitions of the term 'deterrence'.[13] The five NWS under the NPT have since tried to develop a glossary of shared nuclear terms, but the results are neither comprehensive nor unambiguous. While the glossary often uses the term 'verification', it makes no attempt to define it. Its definition of 'nuclear disarmament' can be interpreted either as an end-state, or the actions needed to create this end-state.[14]

Any multilateral verification agreement for nuclear disarmament will have to generate clear and accepted definitions for key concepts and activities. Essential groundwork can be carried out for this by simulating a negotiation process for such agreements to reveal any conflicting interpretations of common terms such as 'information barrier' or 'managed access', and to propose new robust definitions that could apply to future multilateral approaches to disarmament verification.

### Legal compatibility

As discussed in Section 4, states parties entering into a multilateral verification agreement may be subject to a number of pre-existing legal restrictions that constrain the type of verification activities they can commit to. These can include domestic legislation on the handling of sensitive information, and regulations on health, safety, and security at relevant facilities. For example, NWS under the NPT undertake not to transfer nuclear weapons, nor to assist or encourage any NNWS under the NPT to manufacture or otherwise acquire nuclear weapons. A NWS therefore cannot commit itself to disarming by transferring nuclear weapons to any other party. Neither can it commit to verification provisions that would in any way assist or encourage a NNWS to pursue or acquire nuclear weapons.

Verification agreements (be they real or hypothetical) provide a valuable opportunity to identify unexpected legal compatibility issues by providing a codified understanding of an entire verification system, rather than just informal understandings of aspects of such a system. They therefore also provide an opportunity to develop novel solutions to legal issues that might be raised by future multilateral approaches to disarmament verification. For instance, there is no established legal procedure in the NPT to describe how a nuclear-armed state might transition into a NNWS through disarmament. A state that has dismantled nuclear weapons may be considered a NNWS, but aspects of the reporting and safeguarding obligations that come with this designation may be incompatible with its NPT obligations not to reveal information regarding the proliferative or sensitive outputs of nuclear weapon dismantlement.

## Agreed procedures

A wide range of procedures may have to be undertaken under any one disarmament agreement, and an even greater array of verification tasks may have to be carried out to confirm that these procedures are complete. Arms control and disarmament agreements can take months to draft and can run to hundreds of pages. The bilateral New START Treaty—which limits the strategic nuclear arsenals of the US and Russia—runs to a total of 356 pages. These pages include the main treaty text that spells out the basic undertakings of the parties, a verification protocol to be implemented reciprocally by both parties, and three annexes on specific procedures.[15] The verification protocol alone comprises 165 pages of agreed definitions, inspection activities, information exchanges, and consultation procedures.

Multilateral agreements for the verification of nuclear disarmament could require even more detail. If such an agreement were to emerge, it would likely come about through a structured consideration of certain verification activities, linked explicitly to certain disarmament activities. These may be examined in isolation, with the aim of feeding shared understandings into a broader and more inclusive process.

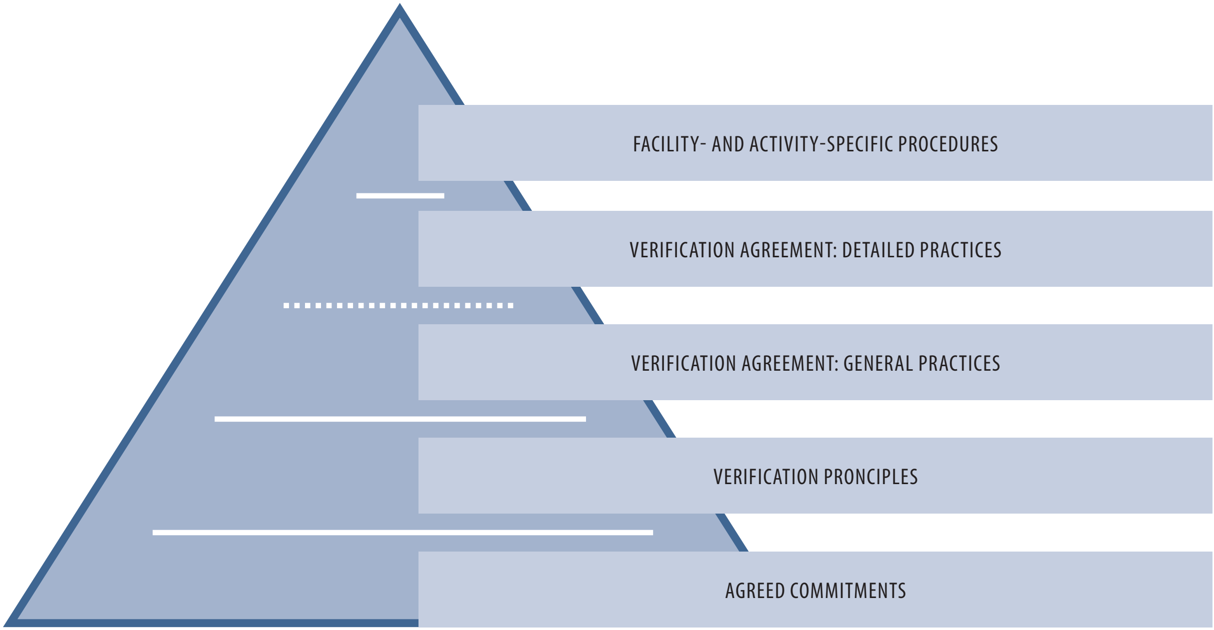
Simulations can replicate this process by generating hypothetical cases of nuclear disarmament for the purpose of exploring the legal issues associated with designing a system to verify disarmament activities. These simulations can then generate a shared understanding of agreeable verification procedures in the form of agreed texts, legal commentaries and simulation reports that explain systematically how the outputs were arrived at. While the hypothetical political and technical factors that influenced the choice of procedures within the simulation may not apply in the real world, the lessons-learned and language generated can serve as a foundation on which less context-specific model agreements could be developed.

## Simulating the development of common understandings and verification agreements

Section 4 outlines a generic structure of verification agreements. This structure provides a stepwise process for identifying and coordinating the provisions that could ultimately define a verification regime. This structure, illustrated in Figure 4.2, and repeated below in Figure 5.1, provides a useful lens through which to consider the simulation of negotiations for a multilateral verification agreement.

The first step is to consider what commitments will be the subject of verification. These commitments must be considered within a credible political context. A second step involves outlining the broad objectives of verification in this particular scenario, as well as the tools that might be available to achieve these objectives. The level of detail required in this step depends on exactly what objectives the simulation aims to achieve. A third step involves considering how the simulated negotiations should produce a useful output that is consistent with the chosen scenario. This may be in the form of agreed, detailed verification procedures, or more general lessons and impressions regarding the negotiation of multilateral verification agreements.

**Figure 5.1** A generic structure for verification agreements



## Establishing a political and technical context

As discussed elsewhere in Section 5, simulations cannot provide an accurate representation of a chosen scenario unless players act only according to that chosen scenario, rather than according to any preconceptions they might hold. Players therefore require detailed and credible backstories for the negotiations, and for the roles they are meant to adopt within the negotiations. These backstories must explain the scope of a player's role, and the motivations behind it. Backstories must also provide a coherent and credible technical environment that describes the respective nuclear capabilities, facilities, and materials that are relevant to a chosen scenario. Methods for developing these political and technical contexts are described in Sections 6.1 and 6.2. Contextual issues that are particularly important for the negotiation of verification agreements include:

- The existence of other relevant treaty or agreement obligations. Participants must be aware of potential issues relating to legal conflict.
- Domestic procedures concerning the negotiation and implementation of verification provisions. Participants must be aware of domestic constraints that affect the scope of acceptable verification arrangements, and the national measures that can be drawn on or created for implementing them.
- The political and technical pressures associated with gaining or conceding ground on certain verification activities, such as the provision of information and access.

## Defining the objectives of a simulation

The value of a simulation is closely related to the clarity of its objectives, and the manner in which a simulation is constructed to achieve these objectives. The generic structure of verification agreements described above presents a challenging array of potential simulation tasks. While it is possible to undertake all of these tasks simultaneously—negotiating everything from an array of agreed commitments through to activity- and facility-specific verification procedures—it may not be practicable. Rather, simulations that focus on a narrow range of pre-determined disarmament activities, and seek to obtain a realistic level of detail, are more likely to produce useful results.[16] The focal point of any simulation should take into account any broader research goals. These may centre on verifying a particular disarmament activity, or on trialling a particular verification technique. Potential simulation objectives include:

- The negotiation of basic verification principles for a broad range of disarmament activities;
- The negotiation of general verification practices for an agreed disarmament activity that may occur at a range of sites or facilities; and/or

- The negotiation of site- and facility-specific procedures to verify a single disarmament activity, to be undertaken at a pre-defined facility, according to pre-defined verification practices.

## Research questions

It is important to consider how a simulation can be designed to successfully meet chosen objectives. One approach is to translate the objectives of a simulation into formal research questions. Research questions can guide the implementation and recording of a negotiation simulation. For example, a simulation which aimed to develop agreed verification practices for an array of disarmament activities that can subsequently be developed into site- or activity-specific verification procedures, may generate the following research questions:

- Which verification practices, ranging from the analysis of environmental samples to the use of third-party intelligence information, are players likely to find the most contentious or trivial for a chosen scenario?
- What positions might various players be expected to adopt on these particular practices?
- What compromises or alternatives might players pursue?

These research questions can form the foundation for a simulation observation scheme. Simulation controllers can translate these research questions into tasks for players to complete within a simulation, and identify key aspects of a simulation that should be observed closely, by drawing initial hypotheses from these research questions that a simulation can then test. The attention of players can be focussed onto their tasks by creating draft or outline negotiation texts (discussed below) that include potentially controversial verification provisions, or ambiguous definitions that players should explore.

## Observation schemes

These research questions can form the foundation for a simulation observation scheme. This scheme would provide simulation observers (who are not active players in the simulation) with instructions on how to record observations, collect feedback from players, and evaluate the simulation as a whole. Techniques for observing a negotiation simulation include:

- Continuous note-taking by designated observers;
- Questionnaires to be completed by participants prior to, during, or after a simulation;
- Discussions and presentations on the views of participants regarding suitable verification arrangements, key legal challenges, and other insights, prior to and after a simulation; and
- The recording of negotiated language and any agreed text or provisions.

## Generating negotiation texts

The political and technical contexts described above, as well as the established research goals, can be conveyed to simulation participants through an outline or draft hypothetical disarmament treaty or agreement. A draft agreement can reflect the political context of a chosen scenario (as discussed in Section 6.1), incorporate the technical details of relevant disarmament activities (as discussed in Section 6.2), and provide a solid foundation on which to simulate the negotiation of verification provisions. For example, a simulation cannot explore the negotiation of site- and facility-specific procedures to verify a certain disarmament activity (the third objective above) unless players have a shared understanding of what that activity involves, and what general verification principles they should follow. A simulation can convey this information to participants through a pre-determined disarmament agreement, which has notionally been agreed by simulation parties. As discussed above, while a simulation could explore the formulation of a complete verification system from the negotiation of agreed disarmament activities to site- and facility-specific provisions, this would be impractical. Creating draft or framework texts can facilitate the simulation of negotiations by focussing players on chosen objectives and specific language.

These draft or framework texts should recognise the political and technical contexts that define the disarmament scenario being simulated. Methods for developing these contexts are described in Sections 6.1 and 6.2. A common structure for such agreements typically includes an opening preamble describing the objectives and principles of the agreement; opening articles outlining the basic undertakings; subsequent articles providing greater detail of these undertakings; articles describing any agreed verification principles or practices; and articles describing administrative issues relating to confidentiality, entry-into-force, withdrawal, and dispute resolution. This structure can be populated by adopting and adapting language from existing agreements, such as those listed in Box 5.2 below.

### **Box 5.2** Existing agreements that can contribute to hypothetical agreements

- The Joint Comprehensive Plan of Action (2015), between Iran and the E3/EU+3;
- United Nations Security Council Resolution 687 (1991);
- The African Nuclear-Weapon-Free-Zone Treaty (Pelindaba Treaty) (1996);
- The Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction (Chemical Weapons Convention) (1993);
- The Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation (as amended) (2010);
- Notional Model Agreement Between <a State Possessing Nuclear Weapons> and the International Atomic Energy Agency for Verification in Relation to Disarmament.[17]

## 5.4 Informing nuclear disarmament verification policy

Previous sections have discussed how simulations might explore the multilateral verification of hypothetical disarmament scenarios. These simulations can examine questions that are specific to a certain disarmament activity, such as the technical suitability of a verification system and the manner in which such a system could be codified into a verification agreement. Simulations can also explore more general issues relating to the multilateral verification of nuclear disarmament, such as the political desire among nuclear-armed states to consider multilateral verification, and who might be involved in it.

It is important to consider whether nuclear-armed states would actually pursue multilateral verification of any future disarmament activities. As discussed in Section 6.1, it is possible to generate a number of hypothetical scenarios in which a disarming state would indeed pursue multilateral verification. Multilateral approaches to verification can generate greater confidence among more parties than bilateral or unilateral efforts to demonstrate nuclear disarmament (as discussed in Section 2). However, a purely hypothetical scenario of multilaterally-verified nuclear disarmament—which incorporates none of the political, technical, and legal issues that affect nuclear disarmament in the real world—will do little to build confidence among states that such verification would be desirable in the real world. This can only be achieved by incorporating real world issues into hypothetical scenarios, thereby gradually bringing a simulation closer to reality.

These general issues relate not just to how multilateral verification of disarmament should be carried out in any specific scenario, but also to who should conduct this verification in general, and how they should prepare for this role. There are a number of possibilities regarding who would ultimately be party to any multilateral agreement to verify nuclear disarmament. These include the use of an intergovernmental organisation, which represents its member states, or a group of states, or a combination of the two. While the IAEA has a statutory mandate to verify nuclear activities on request, a number of questions remain over its current ability to carry out this mandate in all circumstances. Member states have noted in a resolution to the General Conference that 'the Agency must remain ready to assist [. . .] with verification tasks under nuclear disarmament [. . .] that it might be requested to carry out',[18] but have not yet specified which verification tasks they envision, nor pressed for an assessment of the agency's current readiness. Exploring who might undertake multilateral verification and how that actor should prepare for such a role, can build confidence among nuclear-armed states and non-nuclear-armed states alike that there are credible and reliable approaches to the multilateral verification of nuclear disarmament. As discussed in Section 2, the promise of such verification can incentivise nuclear-armed states to pursue disarmament.

The previous two sections have discussed how scenario-specific simulations can explore technical and legal issues associated with multilateral verification of nuclear disarmament. This section builds on this discussion to explain how scenario-specific simulations can explore more general political issues behind multilateral verification of nuclear disarmament, and demonstrate its promise as a credible and reliable verification system.

## Generating debate

There is strong support among some IAEA member states for an agency role in verifying nuclear disarmament. The IAEA General Conference has heard supportive statements from member states such as Brazil, Cuba, Egypt, Sweden, and Turkey. These have been augmented by Working Papers submitted by groups of NPT NNWS such as the New Agenda Coalition and the Non-Aligned Movement (representing a combined total of 124 states) during the 2015 NPT Review Conference process. This support was most recently manifested at the 2015 General Conference of the IAEA, when member states passed the resolution outlined above.[19]

IAEA member states play a vital role in determining the scope of IAEA involvement in verifying nuclear disarmament. A lack of debate on this issue suggests that there is room for increasing the level of awareness among states of the challenges and opportunities such a role presents. The majority of member states cannot call on the same level of technical expertise and experience as NWS for verifying particular disarmament activities, such as the dismantlement of nuclear weapons. Their representatives are also typically responsible for a broad range of issues, and have little time to consider what is currently an ad hoc and peripheral activity for the IAEA. Addressing this issue requires developing a sound knowledge base and building capacity among member states in the technical and political issues surrounding the multilateral verification of nuclear disarmament, such that they can make a substantive contribution to the debate over the IAEA's role in this area.

Even if states were not to choose the IAEA as the sole or principal body responsible for verifying all aspects of nuclear disarmament, building such fundamental knowledge and capacity will be essential since it will provide states with sufficient know-how to explore alternative arrangements.

## Building capacity through simulations

The simulations described in Sections 5, 5.1, and 5.2 can build capacity among IAEA member states to debate the role of the agency in verifying nuclear disarmament. Developing and implementing these simulations involves a comprehensive evaluation process on the political drivers behind disarmament verification, the technical procedures and equipment underlying disarmament verification, and the legal processes involved in codifying disarmament verification. IAEA member states can contribute to, and participate in, simulations of multilateral verification of nuclear disarmament through a dedicated programme of simulations, or through the integration of simulations into a broader capacity-building enterprise, or both.[20]

### Scenario design

As discussed in Section 6.1, simulations must draw on detailed and plausible scenarios for nuclear disarmament. Developing these scenarios involves considering the circumstances that might lead a nuclear-armed state to pursue nuclear disarmament, and the factors that influence a decision to verify disarmament multilaterally. Involving IAEA member states in this process will generate an understanding of these factors, and the circumstances under which the IAEA might be called to verify disarmament.

### Modelling

The tasks associated with verifying nuclear disarmament are defined by the size and composition of nuclear weapon programmes, and the steps involved in their disarmament. IAEA member states must understand the demands of multilateral nuclear disarmament verification before they discuss what might be required to achieve it, and who should carry it out. States can gain an appreciation of the size and composition of hypothetical nuclear weapon programmes through the modelling described in Section 6.2.

However, this modelling must be carried out in a manner that accommodates the need to accurately portray a nuclear weapons programme with the requirement not to expose proliferative information. While IAEA member states should not be encouraged to explore how nuclear weapon programmes are developed, involving them in the generation and exploration of disarmament activities will help build an important technical understanding of nuclear disarmament verification.

### Participation

Participating in one of the simulations described in Sections 5, 5.1, and 5.2 can provide a detailed appreciation of the challenges and opportunities of multilateral verification of nuclear disarmament. As discussed in these sections, players in these simulations are required to consider the political and technical environment in which disarmament takes place, and work with other players to generate and test a multilateral verification system. Participating states can gain an appreciation not just of the steps involved in multilateral verification of disarmament, but also of the various pressures that come with implementing or being subject to multilateral verification. The UK-Norway Initiative (as discussed in Section 5.2) has demonstrated the value of adopting unfamiliar roles in a simulation of nuclear disarmament verification.

## Preparing for multilateral verification of nuclear disarmament

States will influence more than just the scope of any multilateral arrangement to verify nuclear disarmament. They will also help shape the tools and techniques that might be used to carry it out.

As Section 2 has identified, the IAEA is an important body to consider for multilateral verification activities based on its experience, expertise and mandate. The IAEA Department of Safeguards has included its role in verifying nuclear disarmament within its Long-Term Strategic Plan (2012-2023). One of its overarching strategic objectives is to 'contribute to nuclear arms control and disarmament, by responding to requests for verification and other technical assistance'. To meet its objectives, the Department of Safeguards has developed strategies that cover conceptual, legal, technical, resource, partnership, and communication aspects of its work. However, the work it conducts to prepare for nuclear disarmament verification is currently limited to technical aspects of its work, where it plans to maintain readiness to provide technical expertise for, or to verify, nuclear arms control and disarmament.

The IAEA's current Programme and Budget suggests that the agency is only preparing to verify nuclear disarmament activities in the Democratic People's Republic of North Korea, and between the US and Russia under the Plutonium Management and Disposition Agreement. The agency's success in this endeavour depends on the guidance and support of IAEA member states. This support, typically given through IAEA Member State Support Programmes, can simulate multilateral approaches to explore the role of monitoring equipment in nuclear disarmament verification (as discussed in Section 3) and develop technical approaches to verification (as discussed in Section 5.2). Simulations of multilateral verification of nuclear disarmament can also highlight new or unexpected issues with an IAEA role in this activity, and inform the agency's broader efforts to achieve its Long-Term Strategic Plan.

## Shaping the research agenda

As discussed in Section 5, the value of a simulation is closely related to the clarity of its objectives and the manner in which it achieves these objectives. A single simulation might aim to test the effectiveness of a certain piece of equipment in overcoming an expected verification challenge (see Section 5.2), or it might aim to develop politically acceptable principles of verification for a broad array of disarmament activities (see Section 5.3).

Member State Support Programmes are voluntary endeavours, informed by the IAEA's research and development needs as communicated through the agency's Research and Development Programme for Nuclear Verification. This Programme can generate a number of research questions that can serve as the objectives for tailored and focussed simulations. The results of these simulations can in turn inform the IAEA's research and development needs, generating a dialogue between the IAEA and its member states on the multilateral verification of nuclear disarmament.

Outside of the IAEA, states can develop individual or collaborative initiatives to explore multilateral verification of nuclear disarmament. Some activities are underway. The UK-Norway Initiative focuses on the verified dismantlement of nuclear warheads. Other initiatives include the European Commission's Joint Research

Centre (which coordinates nuclear science research in support of EU policy) and the European Safeguards Research and Development Association (ESARDA), (which harmonises research among European safeguards organisations). The nascent International Partnership for Nuclear Disarmament Verification (IPNDV), created by the Nuclear Threat Initiative and the US Department of State, will also seek to catalyse and coordinate research into disarmament verification. VERTIC's project through which this compendium has been produced, seeks to provide a holistic study of how nuclear disarmament can be verified multilaterally and how capacity can be built to achieve this.

Simulations of multilateral verification can contribute to the broader research agenda of nuclear disarmament and verification in general, by testing equipment and procedures, identifying new challenges, and developing a common understanding of the issues among key stakeholders.[21] In this manner, states can shape the agenda of research into multilateral verification of nuclear disarmament through coordinated simulations, where the results of one experiment can influence the objectives of another—irrespective of whether these simulations are carried out individually or collectively.

## Building confidence in multilateral verification

Multilateral verification can be carried out by a collection of states, or by an intergovernmental organisation, such as the IAEA, that represents such a collection states, or a combination of the two. In contrast, bilateral verification is carried out by only two states—typically in a reciprocal situation where both have agreed to the same commitments. Despite the broader level of assurance that can be achieved through multilateral verification, the IAEA is not the default verification body for nuclear disarmament. For example, while the IAEA has a mandate to verify nuclear disarmament (as discussed in Section 2), this mandate only extends to scenarios in which it is requested to do so. Such a request could come directly from States Parties, or from UN Security Council Resolutions. Aside from a ruling from the International Court of Justice, there are no other methods to require IAEA verification of nuclear disarmament.

While IAEA member states can influence the scope of the agency's role in verifying nuclear disarmament and the tools and techniques it can use to achieve this, the agency's ability to carry out this role depends on co-operation from a disarming state. Their willingness to subject future disarmament activities to multilateral verification depends on whether they feel the benefits of broader assurance provided by a multilateral approach to verification outweigh the potential costs or complications such an approach might incur when compared with a simpler and more manageable bilateral verification relationship. As discussed in Section 2, demonstrating that multilateral verification can build assurance in disarmament may increase support for multilateral disarmament verification among nuclear-armed states.

The simulations discussed in Sections 5, 5.1, and 5.2 address the multilateral verification of specific hypothetical scenarios of nuclear disarmament. While these can develop and refine tools, procedures, and agreements for multilateral approaches to disarmament verification, they may only provide limited confidence to nuclear-armed states concerned with real, rather than hypothetical, scenarios of nuclear disarmament. This is an unavoidable downside of all simulations, which by definition draw on approximate representations of reality. Nevertheless, simulations can integrate features from current real-world disarmament initiatives to provide useful and credible insights into the effectiveness of multilateral verification in the real world and build confidence in this approach.

## Developing credible verification regimes for existing disarmament initiatives

As discussed in Section 4.2, nuclear disarmament may incorporate different activities, ranging from the dismantlement of nuclear weapons to the termination of fissile material production for weapons purposes. Some of these disarmament activities appear to be more appealing to nuclear-armed states at the present time than others.

The Plutonium Management and Disposition Agreement (PMDA) between the US and Russia calls on both parties to dispose of 34 metric tonnes of plutonium recovered from nuclear weapons or declared excess to military requirements. Parties will draw on experience and knowledge gained from exercises conducted under the Trilateral Initiative—consisting of the US, Russia and the IAEA—which sought to develop multilateral methods to verify the disposition of plutonium in classified forms. Although the initiative developed prototype equipment and model legal procedures to achieve this verification, neither party to the PMDA has finalised the procedures by which their material disposition will be verified by the IAEA.[22]

The products of the Trilateral Initiative can be introduced into a simulation of multilateral verification to build confidence that agreements such as the PMDA can be successfully verified. Such a simulation could generate hypothetical nuclear-armed states, and place these states within a hypothetical political context in which they would agree to dispose of weapons-usable fissile material. Players adopting the roles of verifying and verified parties can then consider the model agreements and equipment produced by the Trilateral Initiative, and work together to finalise a detailed verification procedure. Subsequent simulations could test this detailed procedure to identify and address its strengths and weaknesses. Drawing the technical and political context of these hypothetical cases closer to reality will generate verification solutions that are progressively more applicable to real nuclear-armed states, and build confidence in these states that such disposition would be in their interest.

This approach can help to develop credible multilateral verification regimes for existing disarmament initiatives, and strengthen support for such initiatives among nuclear-armed states. For instance, France has produced a draft Fissile Material Cut-Off Treaty (FMCT), which lays out the basic undertakings of such a treaty and gives an outline of the verification principles and practices that should be applied. Simulations can play a central role in generating and testing detailed verification arrangements for such a treaty, thereby contributing to broader efforts to negotiate an FMCT that is both agreeable and verifiable.

## Demonstrating credible verification regimes

Ultimately, nuclear-armed states should play an active role in simulations of multilateral approaches to nuclear disarmament verification. As discussed in Sections 6.2.5, it is challenging to develop detailed models of nuclear-armed states without encroaching on proliferative information. It is also challenging to develop politically credible scenarios for nuclear disarmament without understanding the unique drivers that prompt states to acquire and maintain nuclear weapons in the first place. Finally, detailed models and credible political scenarios will never provide a simulation player with the same appreciation of the pressures surrounding disarmament verification than what is felt by real representatives of nuclear-armed states. Participation from nuclear-armed states can remedy these issues.

Nuclear-armed states have participated in simulations of disarmament verification, and indicated that they will continue to do so. The UK and the US have undertaken an array of exercises associated with the verification of nuclear weapon dismantlement since 2000. Separately, the UK-Norway Initiative continues to demonstrate that nuclear- and non-nuclear-armed states can explore issues associated with disarmament verification using hypothetical simulations.

The involvement of nuclear-armed states in further simulations, which move beyond bilateral verification of warhead dismantlement into the multilateral verification of other disarmament activities, will depend on their willingness to engage with questions that may be hard to answer. Concerns regarding the exposure of sensitive technical information regarding their own capabilities, or indeed sensitive political information regarding their own preferences toward disarmament verification, may preclude their involvement in simulations that mirror reality.

These concerns may be overcome by focussing primarily on simulations of purely hypothetical disarmament scenarios. Players in such a simulation may find it hard to infer the technical capabilities or political positions of other players when their roles are abstracted away from reality. Over time, as hypothetical simulations explore and refine acceptable multilateral approaches of verifying nuclear disarmament, concerns regarding the exposure of such information may be addressed and replaced by an enthusiasm to explore nuclear disarmament in the real world.

## Section 5 endnotes

1 For example, it took the US Department of Energy more than a year to gain approval to demonstrate equipment designed to provide unclassified identification of a nuclear warhead component to Russian interlocutors in the 1990s. Less obvious complications—such as the spread of wildfires near the chosen facility—also delayed the demonstration, which was ultimately successful. See: William H. Dunlop, *Thoughts on Verification of Nuclear Disarmament*, CISAC Conference: P-5 Nuclear Doctrines and Article VI, September 2007.

2 Such as the CTBTO Preparatory Commission's Integrated Field Exercises, which test on-site inspection protocols and procedures; CWC challenge inspection exercises; and IAEA safeguards training.

3 It is worth noting that a simulation may demand that some players have more information on these matters than others.

4 The US and the Soviet Union tested monitoring technologies on real nuclear weapons deployed on a Soviet cruiser to explore the identification of nuclear weapons in an arms control context, even if US participants had to attend in a purely personal capacity. See David Cliff, Hassan Elbahtimy and Andreas Persbo, *Verifying Warhead Dismantlement: Past, present, future*, Verification Matters No. 9, London: VERTIC, 2010, pp. 36-39.

5 See *Joint U.S.-U.K. Report on Technical Cooperation for Arms Control*, Washington: Department of Energy, 2015, pp. 14-17.

6 *Agreement between the Government of the United Kingdom of Great Britain and Northern Ireland and the Government of the United States of America for Co-operation on the Uses of Atomic Energy for Mutual Defence Purposes*, Washington, July 3, 1958. Available here: http://www.nti.org/media/pdfs/56_4.pdf?_=1316627913

7 *The United Kingdom-Norway Initiative: further research into the verification of nuclear warhead dismantlement*, Working Paper 31, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2015/WP.31, New York: 22 April 2015.

8 Information barrier technologies aim to filter monitoring information to prevent the release of unauthorized information to observing parties. See Section 3.1 for more information on information barriers.

9 Facilities used include the Institute for Energy Technology in Kjeller, Norway, and the Atomic Weapons Establishment (AWE) in the UK. *The United Kingdom-Norway Initiative: further research into the verification of nuclear warhead dismantlement*, Working Paper 31, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2015/WP.31, New York: 22 April 2015.

10 For a discussion of the methods and limitations of modelling, see Sections 6.2.4 and 6.2.5.

11 Thomas E. Shea and Laura Rockwood, *IAEA Verification of Fissile Material in Support of Nuclear Disarmament*, Cambridge, Mass.: The Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, May 2015.

12 Political circumstances can influence the techniques used to verify disarmament, and the manner in which these techniques are chosen. For example, a disarming party may be compelled to accept the application of intrusive monitoring techniques by the political circumstances that lead to its disarmament. Alternatively, two friendly and trusting states may voluntarily enter into a disarmament agreement that has very few provisions for monitoring and verification techniques.

13 Gregory Kulacki, 'Chickens Talking With Ducks: The U.S.-Chinese Nuclear Dialogue', *Arms Control Today*, September 2011.

14 *P5 Glossary of Key Nuclear Terms*, P5 Working Group on the Glossary of Key Nuclear Terms, Beijing: China Atomic Energy Press, April 2015.

15 Including the conduct of on-site inspections, the provision of notifications, and the provision of telemetric information from missile test launches.

16 As discussed above, this approach also reflects common procedure for the negotiation of arms control agreements, where progress is made through the stepwise creation of individual focussed working groups rather than the collective and simultaneous negotiation of all relevant issues.

17 This model agreement was developed by Thomas E. Shea and Laura Rockwood. See Thomas E. Shea and Laura Rockwood, IAEA Verification of Fissile Material in Support of Nuclear Disarmament, Cambridge, Mass.: The Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, May 2015, Annex B, p. B1.

18 *Strengthening the Effectiveness and Improving the Efficiency of Agency Safeguards*, GC(59)/RES/13, Vienna: IAEA, September 2015

19 *Ibid.*

20 The CTBTO series of Public Policy Courses are a notable example of such enterprises. These courses often conclude with a simulation of deliberations within CTBTO's Executive Council over the exercise of verification tools.

21 Action 19 of the 2010 NPT Review Conference stated that 'all States agree on the importance of supporting cooperation among Governments, the United Nations, other international and regional organizations and civil society aimed at increasing confidence, improving transparency and developing efficient verification capabilities related to nuclear disarmament'. *Final Document of the 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons*, NPT/CONF.2010/50 (Vol. 1), New York: UN, 2010.

22 More information on these can be found in Thomas E. Shea and Laura Rockwood, *IAEA Verification of Fissile Material in Support of Nuclear Disarmament*, Cambridge, Mass.: The Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, May 2015.

# 6. Scenarios and Models: Building a Simulation

Nuclear disarmament is not a monolithic process that will take place in the same manner in all situations. On the contrary, instances of disarmament will differ according to factors such as the size and composition of nuclear weapons programmes, as well as the political conditions surrounding the disarmament negotiations and the relationship between parties. Depending on these variables, disarmament will entail different processes, different demands and even different end-goals. As such, any discussion of ‘nuclear disarmament’ in a general, unqualified sense is bound to maintain a level of abstraction. This is because the precise details surrounding each step of the disarmament process, as well as those who will be involved with it, are highly dependent on the context. In the past, this has proven to be a significant obstacle for moving forward with the debate on verification of nuclear disarmament. This is because verification is a precise discipline and verification solutions are best developed when they focus on specific, actionable information. As discussed in Section 2, establishing contextual ‘boundary conditions’ that provide a well-defined set of parameters to disarmament and verification activities, is one way to bring greater clarity and practical focus to the discussion.

Boundary conditions are especially important for the purpose of setting up and running simulations to explore verification solutions, as they provide crucial information on the environment and background that players will interact with. Without a set of detailed and comprehensive boundary conditions, the simulation will lack authenticity, and players will likely not have enough material to engage with the simulation and to pursue their respective tasks. It is also important that boundary conditions for a simulation reflect and support the simulation’s objectives. For an in-depth discussion of the objectives and requirements of simulations, see Section 5.

In the context of studying verification solutions for nuclear disarmament, boundary conditions can be understood as consisting of different kinds of information, ranging from political and legal considerations to technical data on nuclear facilities and material. This information is captured in two main components, disarmament scenarios and nuclear fuel cycle models.

Disarmament scenarios portray a specific, discrete instance of disarmament, which can be based on existing or hypothetical countries and agreements. These scenarios provide the political and legal context for the disarmament activities. They include both a comprehensive overview of the country’s history, international relations, and approach to nuclear weapons and technology, as well as highly detailed information on the commitments and requirements for disarmament and verification.

Nuclear fuel cycle models, in contrast, represent a country's nuclear fuel cycle, from the acquisition of source material through to weapons production, providing detailed information on individual facilities and on mass flows of nuclear materials. These models aim to provide an alternative method for testing and researching verification solutions, since accessing existing nuclear facilities and material raises issues of safety, security and proliferation, and can present high costs. Nuclear fuel cycle models are prepared through research, calculations and dedicated software, with the aim of providing as realistic a picture as possible.

The process of developing disarmament scenarios is explained in Section 6.1, whereas the methodology for creating nuclear fuel cycle models is presented in Section 6.2. Scenarios and models are presented separately for ease of understanding and exposition, and can be used independently of one another as general tools for research. However, their development is structured similarly, and can proceed in parallel, with the two processes informing each other. As such, the final products can be combined to provide a thorough and comprehensive analysis of disarmament and verification conditions through simulations and other means.

## 6.1 Key characteristics of disarmament scenarios

Part of the task of establishing boundary conditions is to outline a specific instance of nuclear disarmament, with its distinctive context and characteristics. The product of this process is a 'disarmament scenario'. A scenario brings together a range of hypothetical details—such as the parties to a disarmament or verification agreement, and the main commitments to be verified—into a coherent and consistent representation of a possible future disarmament situation. To aid plausibility and consistency, a scenario is also informed by an historical and geopolitical context, charting the state's history, its relationship with other states, and its rationale for acquiring nuclear weapons. This section, and the ones that follow, present a methodology that can be used to develop disarmament scenarios that are plausible, internally consistent, and which can generate useful insights.

### Scenario backdrops: replicating existing and hypothetical situations

A disarmament scenario will centre on one or more disarming states. A range of other actors can also be included, such as international organisations and states with a particular interest in the disarmament process. Those undertaking the development of a disarmament scenario may decide to simulate the precise or approximate conditions of an existing state or instead to create a scenario that does not bear direct similarity to any particular state. Each approach has its merits and is appropriate for different uses and situations.

Scenarios can be used to explore disarmament verification with rigour and a practical focus. By replicating existing situations, scenarios can help gain new insights on key political issues. Considering the importance of issues such as monitoring compliance and the possibility of cheating in discussions on arms control, a study that focused on realistic challenges and opportunities for the effective verification of a proposed agreement would likely be a valuable contribution to the debate. For example, the production of nuclear weapons by the DPRK presents a clear and present challenge for the international community, and in particular, for those concerned with disarmament and verification. Developing a scenario based on the DPRK case could enable a thorough and rigorous examination of the challenges and issues ahead, and facilitate technical and political readiness to move forward with negotiations as soon as the opportunity presents itself. A 'needs-assessment' exercise based on such a scenario could be of particular value to any bodies likely to have a direct role in the verification process, such as the IAEA, whose involvement has been proposed in the past and which is already preparing for such a role (see Section 5.4).

Furthermore, governmental and international bodies whose duties encompass verification could use such a scenario for planning and training purposes. This can be useful to build capacity before verification measures are implemented, such as the CTBTO's on-site inspection training through its Integrated Field Exercises.[1]

Developing scenarios based on more hypothetical situations requires a significant creative effort to achieve plausibility and consistency, but scenarios of this kind can offer several benefits of their own. The first advantage is that hypothetical scenarios can be more suitable for public work. Scenarios based on existing situations can touch on political sensitivities, as they analyse a country's history of proliferation and nuclear infrastructure, and speculate on important political choices that the country may make in the future. Hypothetical scenarios, on the other hand, can facilitate discussion of specific technical and political issues on neutral ground, which can be especially valuable for use in simulations and training aimed at a diverse, international audience. Furthermore, scenarios based on hypothetical countries allow greater flexibility to bring certain issues into focus. For example, scenario developers may want to explore how a particular legal requirement or political element may influence verification procedures in general, or may want to introduce a specific inspection technique, to explore its applications. In such a case, a fully hypothetical scenario can be used to put the issue front and centre, and have the research, or the simulation, address it in detail.

The two approaches outlined above do not have to be distinct: hypothetical scenarios can be partially based on existing countries and situations, changing only some of the key components and removing the direct association with contentious political issues. This can be helpful for exploring specific questions pertaining to a real life case in a more neutral setting.

All scenarios, even those built on existing states and political conditions, are necessarily built on a degree of speculation, since they essentially describe one of the many ways a current political issue could evolve. While they can provide a robust account to draw on, they are not immune to the risk of inaccuracies or inconsistencies. For this reason, it is crucial that disarmament scenarios measure up to rigorous standards.

## Requirements for the creation of disarmament scenarios

It is important to acknowledge that a study conducted under this methodology will yield results that are only as good as the premises and assumptions they are built on. The three main requirements are detail and comprehensiveness, logical consistency, and realism.

First, it is necessary that boundary conditions are comprehensive and provide all the fine detail that is necessary to consider the practical aspects of the problem at hand. A scenario that is incomplete may result in researchers missing fundamental problems, or ignoring important issues. This is especially true for research that looks at disarmament verification on a wide scale, covering a number of weapons of different types and many facilities at all stages of the nuclear fuel cycle. For example, establishing clearly in what ways a country has kept records regarding its fuel cycle, or detailing the life cycle of individual facilities in the country's nuclear fuel cycle, may not immediately seem relevant for the purpose of researching verification solutions. However, this information is necessary to develop procedures that inspectors may use to verify the production path of fissile material, and to ensure the long-term irreversibility of disarmament. Similarly, having clear definitions of what items are accounted for under a treaty (existing or hypothetical), and in what ways, is crucial for verification purposes.

Furthermore, comprehensiveness is required to make sure that all assumptions about the scenario are clear and explicit. Any important detail that is not defined in advance is liable to be 'filled out' by the implicit assumptions and biases of researchers or participants to a simulation. This may lead to inaccuracy, misunderstandings and consistency issues. If the characteristics of the scenario are spelled out with precision and detail, these can be easily reviewed, and any research or simulation based on these premises can be repeated. This is the best way to test the scenario for inaccuracy, bias or inconsistency, and if necessary, correct the course constructively.

Logical consistency is a very important issue: it is crucial that scenarios are internally consistent and respect their own premise. A scenario that contradicts itself may be useless for the purpose of researching verification solutions, or even worse, it may produce results that are not applicable to real life. This is especially important when scenarios are used to set up simulations for training and education purposes, as flawed results could be mistaken as being valid, and provide misleading lessons and examples.

As a final requirement, scenarios need to be credible and realistic for the results to be relevant and applicable to possible real-life cases in the future. Verification solutions based on a scenario that would likely never take place in real life would add little value to the debate on nuclear disarmament verification. While almost all scenarios involving nuclear disarmament require a certain measure of speculation and uncertainty, it is important that they are built on situations that may plausibly take place in the future.

## Scenarios as a tool for researching disarmament verification

Of course, there is no way to guarantee that a certain future scenario, even one that looks overwhelmingly plausible, will really take place. Furthermore, future disarmament arrangements may follow a scenario's general concept, but diverge from it on several details and characteristics. The main advantage of using scenarios to explore verification issues is not an ability to accurately predict the future, but rather, a structured framework to analyse the political and technical factors involved in nuclear disarmament, and ultimately the main challenges for verification presented by a specific situation. While this work mainly concentrates on using scenarios as a backdrop for simulations, they can also be used to inform desk research or expert discussions, in order to focus on specific, practical challenges.

It is important to note that no individual scenario can be used to explore all the technical and conceptual tools that future verification arrangements will require. Since these arrangements will be built on the specific goals and constraints presented at the time, creating a 'general' scenario to accommodate all possible requirements would reintroduce the problem of excessive abstraction. Instead, building a series of disarmament scenarios makes it possible to examine a range of different possible situations, and to consider the application of verification techniques in different contexts.

Specific inspection procedures and technologies could be put front and centre in more than one scenario, and set against different backgrounds. For example, it would be useful to explore how a regime of complementary access could be applied to the inspection of a diverse and distributed fuel cycle presenting mixed public and private ownership, and to contrast it with how similar provisions would be applied to a fuel cycle exclusively owned by a country's military. This sort of comparison would yield precious insights on how to apply a specific verification technique to a whole range of different situations.

This type of process can also be useful for those verification tasks that are considered to be universal, such as the verification of a baseline declaration, or the establishment of continuity of knowledge throughout the weapons dismantlement process. While these steps are likely to be involved in all, or almost all verification arrangements, the operational details of how they are implemented are likely to be affected by the facilities and devices they are applied to, as well as by the surrounding political context. By testing how these steps would play out in different scenarios, researchers and participants to simulations can derive insights that may be useful in the future, and possibly identify general best practices that can be referenced to in most, if not all, situations.

The following sections outline the process for creating disarmament scenarios, focusing on the type of information and level of detail disarmament scenarios should include.

## 6.1.1 Scenario development: establishing context for disarmament

Disarmament scenarios are used to focus the examination of nuclear disarmament verification on specific and practical issues. To do so, they present in detail a situation in which a country or group of countries, existing or hypothetical (see Section 6.1), have committed to give up all or part of their nuclear weapons programme in a verified manner. However this is only a snapshot of the final stage of what would be a longer story in reality, one that effectively starts with a country's decision to pursue nuclear weapons. Factors such as the way in which the country acquired nuclear technologies and weapons, the role these had in the country's military planning, and the country's broader history of relating with neighbouring states and global powers, all contribute to shape the end point of disarmament in a significant way. Creating a scenario without having a clear idea of these background elements may result in inconsistencies, or may present elements that, while reasonable on their own, are difficult to justify in the larger context, and thus make it implausible. Furthermore, it is important to remember that scenarios must respect the requirements set out in Section 6.1. The process for developing scenarios and the structure of the final product are described in Box 6.1, below.

The process outlined in Box 6.1 applies equally to scenarios representing either existing or hypothetical countries or situations. For scenarios based on existing countries, the required information can be gathered through research into the country's history. In the case of hypothetical scenarios, an element of creativity is required, in order to generate the fictional country and situation. However, this does not mean that creating hypothetical scenarios does not involve any research on cases of nuclear proliferation and on disarmament agreements. First, a hypothetical scenario may aim to replicate specific aspects of an existing country or situation, or a possible future for the country: in this case, of course, those aspects need to be captured accurately.

**Box 6.1** The creation and anatomy of a disarmament scenario

Scenarios are created by establishing general characteristics first, and then adding levels of detail and specificity. This process is divided into three main steps, each producing a specific document:

- The first step of the process consists of drafting a country profile, which outlines the scenario's main characteristics. This outline does not provide much detail, as its purpose is to narrow down and make explicit the main goals and assumptions behind the individual scenario, in order to provide a guide and reference for the following phases of development.
- The second step is charting the context of the disarmament activities. This features a detailed narrative on the country's history, its position in the international arena, and its development of nuclear technology. The disarmament context document provides background knowledge necessary to inform the finer detail of the disarmament scenario, as well as additional contextual information that can be referenced for in-depth analysis or during simulations.
- The third step consists in preparing the disarmament specification document. Whereas the disarmament context document provides a very comprehensive look at the historical and political context of the scenario, the disarmament specification document focuses on the precise details of the disarmament arrangement, which are of immediate importance when discussing disarmament agreements and verification protocols and procedures.

Taken together, the country profile, the disarmament context document, and the disarmament specification document form a disarmament scenario.

Second, even in the case of hypothetical scenarios that do not aim to reproduce an existing country, researching different case studies of nuclear proliferation and disarmament is necessary to provide parallels and inform the creation of the scenario.

This section describes the first two stages of the process: the creation of a country profile and the charting of a disarmament context document. The disarmament specification document is discussed in Section 6.1.2.

## Country profile

The first stage in laying the groundwork for crafting a disarmament scenario is to outline a country profile. The country profile provides an initial outline of the country's background and the disarmament arrangements, in very general terms, to guide the development of both disarmament scenarios and nuclear fuel cycle models (see Section 6.2). The profile can also be used to pin down specific elements that need to be addressed by the simulation (see Section 5). Since country profiles are only meant to capture the most relevant characteristics of each scenario, they do not follow a rigid template: rather, a 'brainstorming' type session may be more appropriate, as each scenario will focus on different elements. These elements could be political or technical constraints, or specific goals of the verification process. Generally, some of the broad areas that need to be considered at this stage are:

- The general size of the country's nuclear weapons arsenal;
- Key characteristics of its nuclear fuel cycle;
- The type of country: dimension, general economical and political outlook;
- Relationships with neighbouring states and the international community;
- Specific characteristics of the agreed disarmament process;
- Specific requirements or obstacles in the verification process.

Box 6.2 lists two example country profiles developed for two scenarios that VERTIC prepared while investigating disarmament verification methodologies. The box shows that, even at the level of a preliminary sketch, the profiles for example countries 1 and 2 promise to be very different cases, and may highlight different challenges and solutions to verification problems.

For country profiles replicating existing countries, there may be ample historical information available to prepare the country profile. In this situation, scenario developers may want to make specific choices on which

**Box 6.2** Two sample country profiles

**Example Country 1 Scenario:**

This is a scenario based on a hypothetical country, focused on exploring global nuclear disarmament and a ban of fissile material production.

- Example Country 1 is a nuclear-weapon state under the Non-Proliferation Treaty;
- It has a medium-sized, technologically advanced nuclear fuel cycle;
- It possesses approximately 100 nuclear weapons of advanced design, making it a small but sophisticated arsenal;
- A Fissile Material Cut-off Treaty is already in force at the time of disarmament;
- Example Country 1 has agreed to complete nuclear disarmament, under a multilateral treaty that has been signed by all other nuclear-armed countries;
- The disarmament agreement requires a complementary access regime to be established as part of its verification procedures (the complementary access regime is modelled after the procedure of the same name contained in the IAEA Additional Protocol).

**Example Country 2 Scenario:**

This is a scenario based on a hypothetical country and situation, with very strong parallels with the existing case of the DPRK.

- Example Country 2 is a Non-Proliferation Treaty outsider;
- It has a small nuclear fuel cycle, which includes plutonium production through spent fuel reprocessing;
- It possesses a small nuclear arsenal, which it acquired relatively recently;
- It adhered to a unilateral disarmament agreement;
- Example Country 2 is an isolated country, with adversarial relationships with its neighbours and several world powers;
- Verification will take place in difficult political conditions: Example Country 2 may resist any verification measures it perceives as excessively intrusive. Furthermore, trust levels between the parties are low, and there is a high degree of pressure from the verifying parties on the verification process to provide high confidence in its results.

elements and issues to focus on. The scenario will ultimately portray an, as yet, hypothetical situation, in the form of the disarmament process. Marking down the key components of this hypothetical situation will provide a useful reference to support the creation of a scenario.

When creating profiles based on hypothetical countries, it can be especially useful to conduct a review of comparable case studies. These would consist of historical cases of countries that ran a nuclear weapons programme in the past, focusing on those which share some characteristics with the country profile under development.

For example, if the country profile described a hypothetical sixth NPT Nuclear-Weapon State with a mid-sized arsenal and nuclear fuel cycle, scenario developers may want to look at France, the United Kingdom, and possibly China as examples to draw on. Conversely, in the process of creating the scenario for Example Country 2 (see Box 6.2, above), in addition to studying the case of DPRK (many of whose features Example Country 2 shares), VERTIC also conducted reviews of the nuclear weapons programmes of Argentina, Iraq, Libya, South Africa, and Sweden.

## The context of disarmament

A country profile indicates the general direction in which a scenario should be developed. However, the profile will not be sufficient to provide all details required for a study or simulation and ensure that they are plausible and consistent. The next step in the development of a disarmament scenario is the creation of a full disarmament context document.

The disarmament context document will summarise the history of the country, focusing on the following elements:

- The country's history and international relations;
- The country's nuclear proliferation and strategy;
- The country's nuclear history;
- The context and events leading to disarmament.

Each of these areas, in turn, opens up new questions and requires more detail. Scenarios based on existing states can usually rely on a variety of resources to inform this process. Scenarios based on hypothetical countries, on the other hand, require all this information to be created specifically for this purpose, maintaining high standards of consistency and plausibility. To do this, scenario developers need to draw on different disciplines and fields of knowledge. Furthermore, the case studies outlined above can be drawn on for comparison and to provide examples.

### Country history and international relations

This element of the disarmament context document outlines the country's internal politics, its attitude toward the international community, and its position with regard to a series of important issues, such as the IAEA,

**Box 6.3** Country history and international relations in the scenario context

- What is the type and strength of the country's economy and military forces?
- What type of political regime governs it?
- Which are the main actors the country has relations with? How far are they located from the country in question, and what is their relative strength?
- How did the country position itself during the Cold War?
- Did the country adhere to the NPT? If so, did it develop nuclear weapons before adherence, and is therefore a legitimate NPT nuclear-weapon state, or after adherence, breaking out from the treaty?
- Did the country ever have an IAEA safeguards agreement? If so, of what kind?
- What is the country's general security situation?
- What were the most relevant moments of the country's recent history (wars, peace treaties, changes in regime, achieved independence, etc.)?
- How did the international community react to the country's acquisition of nuclear weapons? How did this reaction affect the country's politics and behaviour?

the NPT, and other key arms control treaties. It also describes the country's material resources and capabilities, in terms of its economy, military, natural resources, and technological advancement. Furthermore, it is necessary to consider the country's security situation, indicating whether it has, or had, any relevant alliance or enmity, and how it relates to the major powers on the global scale. To address these issues, scenario developers need to draw on historical examples and an understanding of political science and international relations theory. Box 6.3 provides an indicative list of questions that need to be considered when detailing a country's history and international relations.

## Nuclear proliferation and defence strategy

This element of the disarmament context document provides background and detail to the country's decision to pursue nuclear weapons, and explains the rationale behind it. In addition, this element also describes the role nuclear weapons play in the country's strategic outlook. To address these issues, scenario developers need to draw on a good understanding of the main drivers behind nuclear proliferation, as well as concepts of nuclear strategy. Box 6.4 provides an indicative list of questions to be considered when detailing a country's nuclear proliferation and defence strategy.

The following text, taken from the Example Country 2 scenario developed by VERTIC, provides an example of how a scenario developer can elaborate a country's rationale behind its pursuit of nuclear weapons and its thinking about nuclear strategy.

> *'The ruling elites always considered nuclear weapons as an option, exploring the capabilities required without making a formal decision to pursue nuclear weapons. (. . .) After a severe border incident, realising their conventional army was inferior to their neighbouring states', and that they could not count on the military support*

### **Box 6.4** Nuclear proliferation and defence strategy in the scenario context

- When and why did the country embark on a nuclear weapons programme?
- Who took the decision?
- Was the decision part of a long-term plan, or was it the result of a sudden change in policy?
- Was there an event that precipitated the decision?
- Did the country aim to obtain a hedging capability or an ambiguous status? Or did it aim to produce a visible, deployed arsenal?
- What approach did the country take to deterrence?
- What type and number of nuclear weapons did the country intend to produce? What type and number did they manage to produce?
- Did the country develop thermonuclear weapons?
- Which delivery systems did the country aim to develop? Which ones did they manage to deploy?

> *of other regional allies, the leadership of Example Country 2 took the final decision to develop nuclear weapons. Ongoing research into the principles of nuclear explosives was expanded and formalized, and moved into dedicated secret facilities. Only material from its indigenous production was used at that stage. (. . .) Once the decision to develop nuclear weapons was taken, Example Country 2 wanted to acquire a visible, deployed arsenal that would deter both Country C [Example Country 2's neighbour and historical rival in the scenario] and other external powers from invading it.'*

## Country's nuclear history

The history of operations of the country's nuclear facilities is explored in finer technical details through fuel cycle modelling (see Section 6.2); however, more general information about the country's nuclear history needs to be captured in the scenario, as well. The reason for this is that the development and operations of a nuclear fuel cycle are often influenced by political decisions, and can in turn have consequences at the political and international level. Furthermore, the processes of developing fuel cycle models and disarmament scenarios need to inform each other, in order to maintain internal consistency. Discussion of nuclear history in the disarmament context document should focus on the country's development of nuclear technology, and how it went about its nuclear research and development work. It should specify what type of nuclear facilities the

### **Box 6.5** Nuclear proliferation and defence strategy in the scenario context

- When did the country first acquire nuclear technology?
- Did the country acquire nuclear technology through trade and foreign assistance? Were these technologies employed for proliferative purposes? If so, did the supplier explicitly or implicitly know or suspect this?
- Did the country develop its own indigenous technologies?
- Did the country have domestic uranium supplies?
- How extensive was the country's nuclear fuel cycle?
  - Did the country build nuclear reactors? If so, on what scale? Were these only research reactors? Were they used for power, or primarily for the production of plutonium?
  - Did the country develop uranium enrichment technologies?
  - Did the country develop spent fuel reprocessing technologies?
- Which fissile materials did the country use for its weapons development?
- How competent and precise was the country's nuclear programme? Did it run into problems and setbacks? How were these dealt with? For how long?
- Who maintained control of the country's nuclear facilities?
- To what degree were 'civilian' nuclear facilities and facilities aimed at creating material for nuclear weapons separated, if at all?
- What was the country's approach to transparency with regards to its nuclear activities? Did the country build or operate clandestine facilities? Did the country abuse nuclear facilities that had been declared for peaceful use only?

country operated and how these were obtained, as well as provide a timeline of the country's nuclear activities. Scenario developers need to draw on knowledge of different types of nuclear technologies and fuel cycles, and how they evolved over the years, as well as knowledge of how different nuclear programmes were managed. Furthermore, an understanding of how nuclear technology spread through foreign trade and assistance (both legitimate and illicit) is also required. This information is also referenced during the creation of fuel cycle models (see Section 6.2). Box 6.5 provides an indicative list of questions that need to be considered when developing a country's nuclear history.

It is important to note that, given the complexity of the issue, Box 6.5 provides only a small sample of the many questions that can be answered when outlining a nuclear fuel cycle, be it hypothetical or existing. For more information on nuclear fuel cycle modelling, see Section 6.2.

## Context and events leading to disarmament

This element provides the immediate context for the disarmament activities. It outlines the reasons why the country chose to give up its nuclear weapons, as well as the country's stance toward the disarmament and verification arrangements that have been agreed, and what the country hopes to obtain from the process in terms of larger political goals. It also provides similar information regarding the other parties involved in the scenario. As explained above, this document provides broader information on the situation at the time of disarmament, while the disarmament specification document (described in Section 6.1.2) provides specific details that are of use when looking at practical issues. Box 6.6 provides a list of some key questions that should be posed when developing the context around a disarmament decision.

The contents of this part of the disarmament context document partially overlap with the content of the disarmament specification document (see next section). The main difference is that the disarmament specification document focuses on specific, actionable details concerning disarmament and verification, whereas this part provides a narrative overview of the wider context in which these processes takes place. While the contents

### **Box 6.6** Circumstances of disarmament in the scenario context

- What circumstances brought this agreement about?
- Is it part of a broader change in geopolitics between the players?
- Who is involved, and what have the different parties each committed to?
- What, if any, are the indications and expectations regarding the verification activities? What are the parties' confidence levels concerning the agreement?
- What are the specific sensitivities and red lines of the parties involved?
- What does each of the parties involved aim to obtain from this agreement, in terms of immediate gains and larger consequences?

of a disarmament specification document are immediately and directly relevant to precise technical and political issues, this kind of background information is useful to inform decisions in a more general sense. This can be especially important in the case of simulations, where players will need to fully understand not only the terms of disarmament, but also the wider goals and attitude of the parties they represent (see Section 5).

### 6.1.2 Scenario development: specifying the details of disarmament arrangements

A disarmament scenario needs to provide a set of 'boundary conditions' for discussing the verification of nuclear disarmament (see Section 6.1). These conditions are necessary for research on disarmament verification to move away from abstract concepts and to focus on specific issues and worked examples. In a simulation, these conditions represent the many requirements that negotiating teams and inspectors need to consider when drafting and implementing verification solutions. This subsection examines the creation of a disarmament specification document, and provides examples for developers engaged in this work.

#### A template for disarmament specification documents

Since disarmament specification documents provide actionable information of immediate relevance to the disarmament situation, they must be created following a structured, methodical approach. Defining a list of issues that need to be covered ensures that no detail is accidentally omitted, and that all information is presented clearly. Furthermore, applying the same structure when developing each scenario ensures that they will all satisfy the requirements, and makes them more easily comparable and replicable.

The following is an exemplar template that can be used when charting disarmament scenarios. The template is structured as a list of questions about the scenario. The answers to these questions should provide specific information that is relevant when researching verification solutions.

Boxes 6.7, 6.8, and 6.9, below, will provide sample answers to some of the questions in the template, drawn from scenarios that VERTIC prepared while investigating disarmament verification methodologies.

#### Type of disarmament and political context

These questions outline the international situation surrounding the disarmament operations. They tie in with the background described by the disarmament context document (as described in Section 6.1.1) and focus on some specific issues, such as which entity is responsible for verification, and what is the required level of confidence.

1. Is there an international legal instrument for disarmament?
2. What is the country, or what are the countries, of focus?
3. What kind of disarmament activities are taking place?
    a. Is this complete or partial disarmament?
    b. Is this unilateral or multilateral disarmament? How many parties are involved?
    c. Is this reciprocal disarmament? If so, is it symmetrical?
4. Who is conducting the verification activities?
5. What is the state of relations between the parties? Are any of the parties involved former adversaries, or former or current allies? What is the level of trust between the parties? What level of confidence is required from the verification process?

Box 6.7 provides worked examples, drawn from scenarios that VERTIC prepared while investigating disarmament verification methodologies.

### **Box 6.7** Types of disarmament and political context for Example Countries 1 and 2

**Disarmament of Example Country 1:**

3. What kind of disarmament activities are taking place?
    - Complete, symmetrical, multilateral disarmament. All states possessing nuclear weapons agree to dismantle their nuclear arsenals.
4. Who is conducting the verification activities?
    - The IAEA is involved as the competent body for verification.
5. What is the state of relations between the parties?
    - Some of the parties to the disarmament treaty have a past of rivalry and current relations are still marked by occasional tensions. Example Country 1 is a member in good standing of the IAEA and has productive trading and strategic relationships with other countries across the globe. The verification process is required to achieve a level of confidence akin to the one the IAEA requires to reach a 'broader conclusion' on a country.

**Disarmament of Example Country 2:**

3. What kind of disarmament activities are taking place?
    - Unilateral, complete disarmament of Example Country 2. The 'Coalition of Three', composed of [hypothetical countries] Country A, Country B and Country C, are also parties to the Disarmament Agreement.
4. Who is conducting the verification activities?
    - The IAEA is involved as the competent body for verification.
5. What is the state of relations between the parties?
    - Example Country 2 has been brought to the negotiating table after a border crisis with Country C almost triggered a military intervention by a foreign power, [hypothetical country] Country A. It has accepted to renounce its nuclear weapons, but does not want to appear a defeated power being dictated the conditions of its surrender. It will be wary of excessively intrusive proposals.

## Disarmament and verification agreements

These questions provide details on the agreed process of disarmament and verification.

6. What is the agreed time scale for the disarmament operations?
7. Which processes are to be verified?
8. What international agreements (existing or hypothetical) play a role in the scenario? For each agreement, specify its name, timeline of signature and entry into force, parties, and main verifiable obligations.
9. What kind of information is to be provided by the inspected state?
    a. Is there a declaration about treaty accountable items?[2] If yes, what information is provided in the declaration, and when is it provided to the inspecting party?
10. Are any specific verification procedures required by the treaty or agreement?
11. What are the legal limits to the verification inspections? For example, is there an obligation to ensure that no proliferation-sensitive data are released during the verification procedure? Furthermore, has the inspected state raised any political objections or set any specific limits on the nature and extent of verification activities, that the team devising a verification regime must take into account?

## Technical specification and challenges

These questions focus on the technical aspects of the dismantlement process. They also cover some of the long-term technical challenges, such as specific requirements regarding recovered special fissionable material.

12. What are the treaty accountable items in the treaty?
13. How many weapons are affected?
14. Where will dismantlement operations take place?
15. What happens to nuclear material recovered from weapons following disarmament?

## Safeguards during and after disarmament

These questions focus on the state of IAEA Safeguards in the disarming country, during and after the disarmament process.

16. Are there any safeguards in place in the disarming country at baseline[3] (prior to the verification process)?
17. Are there any safeguards requirements for the post-disarmament nuclear fuel cycle?

Box 6.8 provides worked examples, drawn from scenarios that VERTIC prepared while investigating disarmament verification methodologies.

## **Box 6.8** Safeguards during and after disarmament for Example Countries 1 and 2

**Safeguards in Example Country 1:**

16. Are there any safeguards in place in the disarming country at baseline (prior to the verification process)?
    - Example Country 1 has IAEA safeguards in place, including an Additional Protocol, with arrangements similar to those of other NPT nuclear-weapon states. In addition, Example Country 1 is a signatory to a future Fissile Material Cut-Off Treaty. In this scenario, under the FMCT safeguards are extended to all facilities that could be used to produce special fissionable material, including the ones that were previously exempt from safeguards because they were put to military use.
17. Are there any safeguards requirements for the post-disarmament nuclear fuel cycle?
    - The disarmament agreement requires all disarming states to adhere to the NPT as Non-Nuclear Weapon States, and to conclude a Safeguards Agreement, augmented by an Additional Protocol, with the IAEA.

**Safeguards in Example Country 2:**

16. Are there any safeguards in place in the disarming country at baseline?
    - Example Country 2's research reactor and Magnox reactors were once under INFCIRC/66 safeguards, but these were rescinded roughly 25 years before the disarmament agreement was signed. At the time of signing the agreement, Example Country 2 has no IAEA safeguards in place.
17. Are there any safeguards requirements for the post-disarmament nuclear fuel cycle?
    - The disarmament agreement requires Example Country 2 to accede to the NPT as a Non-Nuclear Weapon State and accept IAEA Safeguards, including an Additional Protocol.

## **Box 6.9** Fissile material provisions for Example Countries 1 and 2

**Fissile material provisions in Example Country 1:**

18. Does the scenario include a ban on uranium enrichment?
    - This scenario includes a Fissile Material Cut-Off Treaty, under which states are prohibited from enriching uranium beyond 19 per cent 235U. Verification measures for this ban are already in place under the FMCT.
19. Does the scenario include a ban on plutonium production from spent fuel reprocessing?
    - Under the Fissile Material Cut-Off Treaty, states are prohibited from recovering plutonium from spent fuel reprocessing. Verification measures for this ban are already in place under the FMCT.
20. Does the scenario include disposal of all fissile material stockpiles?
    - No, the Fissile Material Cut-Off Treaty and the disarmament agreement require states parties to place their stockpiles of special fissionable material into monitored storage, under international safeguards. Chemical or mechanical malformation of fissile pits, down-blending of uranium to lower levels of enrichment or similar procedures are not specifically required by the disarmament agreement.

**Fissile material provisions in Example Country 2:**

18. Does the scenario include a ban on uranium enrichment?
    - Under the disarmament agreement, Example Country 2 has agreed to renounce uranium enrichment.
19. Does the scenario include a ban on plutonium production from spent fuel reprocessing?
    - Under the disarmament agreement, Example Country 2 has agreed to renounce spent fuel reprocessing.
20. Does the scenario include disposal of all fissile material stockpiles?
    - At the end of the disarmament process all fissile materials must be in unclassified form, in storage, under joint monitoring by Example Country 2 and by international parties (to be finalised in negotiation).

### Provisions on fissile material

These last questions regard an issue that is not directly tied to disarmament, but is likely to be touched on in a disarmament scenario: the ban on future production of special fissionable materials.

18. Does the scenario include a ban on uranium enrichment?
19. Does the scenario include a ban on plutonium production from spent fuel reprocessing?
20. Does the scenario include disposal of all fissile material stockpiles?

Box 6.9 provides worked examples, drawn from scenarios that VERTIC prepared while investigating disarmament verification methodologies.

## 6.2 Modelling nuclear disarmament

While it is possible to conduct desk-based reviews of the various technologies, procedures and methodologies applicable to future verification challenges, there are currently few opportunities to thoroughly explore any hypothetical verification tasks in practice. The task of testing verification solutions on real facilities and materials is challenging: it is often expensive, legally complicated and politically sensitive (see Section 5). These challenges to conducting practical verification exercises make it difficult for researchers to replicate or refine methodological approaches or to corroborate results.

As mentioned in Section 5, one possible solution for overcoming these impediments is to create simulations that are affordable and easily replicable. These simulations can accurately, but easily, generate a broad range of verification challenges for an equally broad range of hypothetical notional nuclear programmes and a variety of potential disarmament scenarios (as discussed in Section 6.1).

This section provides an overview of how to create hypothetical nuclear programmes in the form of quantitative nuclear fuel cycle models. These models are developed using a combination of open-access information, expert analysis and commentary, and proprietary numerical modelling software. Together, they form representations of military and or civilian nuclear fuel cycles that provide details of fissile material production, use and storage in the modelled state's nuclear history. Each model provides quantitative data on the movement of nuclear material through each stage of the nuclear fuel cycle for any given period of time (usually year-on-year) within the modelled state's history. They describe when facilities are built, how long they operate for and when they are decommissioned. In addition, the models also contain detailed records of the individual operating conditions for each fuel cycle facility and the types and quantities of materials involved.

It should be stressed that the development of these models, although largely a matter of technical knowledge of nuclear facilities and material production, is not completely divorced from considerations concerning the political history of the modelled state. Both scenario development and modelling work advance in parallel in order to provide coherent and internally consistent data of a real or wholly imaginary nuclear weapon state. Together, the model and the scenario form the background and the environment required to run simulations (see Section 5). Coordination between the scenario and model is important in order to maintain consistency. A model that is developed independently to the scenario to which it is attached runs the risk of being equipped with historically inappropriate technologies, or developing a nuclear arsenal of a different size and sophistication and at a different rate than is needed.

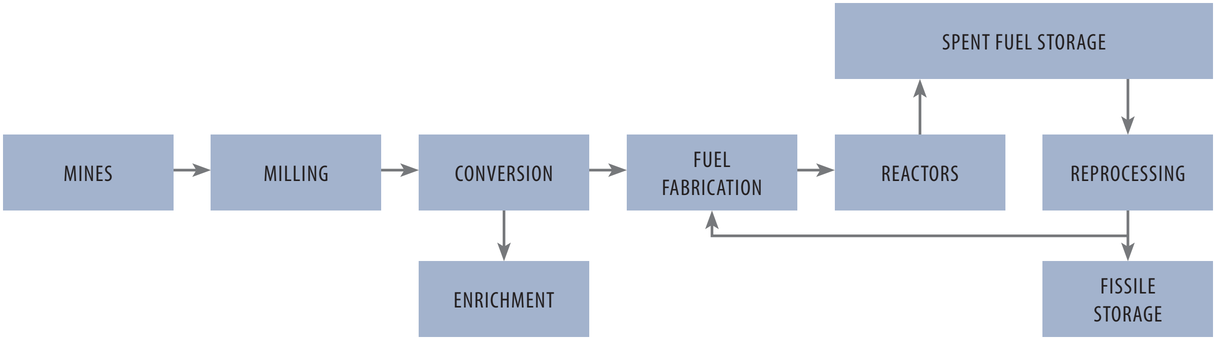
As already discussed in Section 6.1 with regard to disarmament scenarios, modellers, too, need to decide whether to base their models on hypothetical or existing countries. One objective of creating hypothetical nuclear weapon states is to have a model that is representative of an 'unknown' country that is free of any political prejudices or biases that might be projected onto it by users. However, an obvious drawback associated with developing a purely imaginary state is that it becomes difficult to verify its accuracy with regard to what one might expect to experience in a real nuclear weapon state. This is especially true when one considers the various elements that contribute to a nuclear weapon state's development history.

The models and the methodologies described in this section have utility that extends beyond investigations into multilateral approaches to disarmament verification. While they principally provide details intended for exploring dismantlement of nuclear weapons and the subsequent safeguarding of fissile and weapons-usable material, these models could be used for other purposes. For example, once matched with a different set of scenarios, the models could form a platform for exploring verification options in situations where military programmes are merely scaled down, restrained or where parts are discontinued; facilities are converted to civilian use or otherwise decommissioned; or previously undeclared activities or materials are put under safeguards.

### 6.2.1 Generic features of nuclear fuel cycles

In order to create comprehensive and realistic nuclear fuel cycle models, it is first necessary for modellers to understand the nuclear fuel cycle in its entirety and the various chemical and mechanical processes involved. Such cycles can differ in terms of the fuel they use, how the fuel is produced, the fuel's history in the reactor and the manner in which it is managed once removed from the reactor core. This section provides an overview of the various stages of the nuclear fuel cycle and describes the processes and facilities that are used in the generation of electricity for civilian purposes, and for the production of weapons-usable material for nuclear weapons.

**Figure 6.1** Example of a civilian nuclear fuel cycle



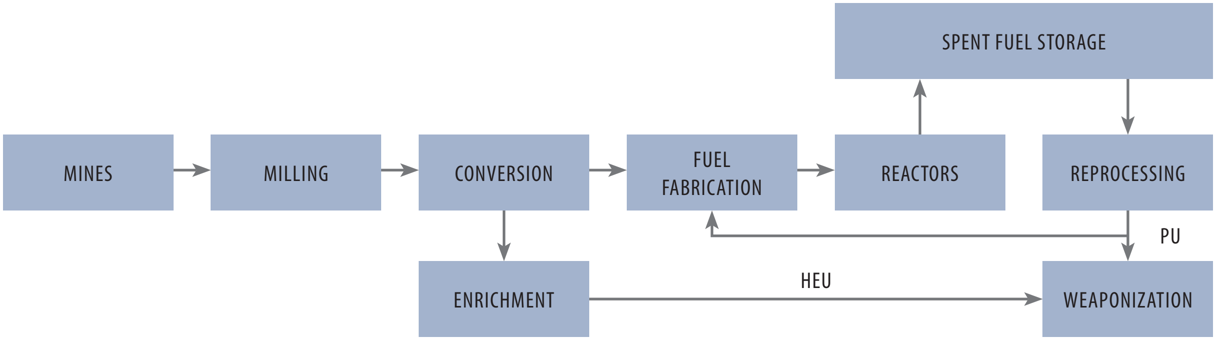
The nuclear fuel cycle is an industrial process involving various activities and facilities that contribute to the production and use of weapons-usable material. The 'front end' of the fuel cycle starts with mining natural uranium ore and progresses through milling, conversion, enrichment and fuel fabrication, after which the fuel is irradiated in a reactor either to produce heat for electricity generation or to produce plutonium for nuclear weapons. The 'back end' of the fuel cycle deals with the reactor fuel once it has been irradiated for a desired period of time. Once discharged from the reactor, the spent reactor fuel may be cooled and stored before undergoing reprocessing and recycling before the waste is finally disposed of.

As the description above indicates, the nuclear fuel cycle invariably comprises technologies and applications that are dual-use by nature. The same facilities and activities can be used to generate electric power for civilian use, to produce material for use in weapons programmes, or both; see Figure 6.1 for an example of a fully civilian fuel cycle, and Figure 6.2 for an example of a fuel cycle in which nuclear materials are used for the production of weapons.

## Uranium extraction and milling

Uranium, the raw material in nuclear fuel, is an abundant metal that can be found across the world. Generally speaking, the average concentration of uranium in the Earth's crust is about 2.8 parts per million. The element is present in most rocks and soils and even in rivers and seawater (though, in this case only in trace amounts of 3-4 parts per billion).[4] Uranium is roughly 500 times more abundant than gold and about as common as tin. At least 46 states have natural reserves of recoverable uranium, but, as of 2014, 54 per cent of the world's uranium came from just ten mines in six countries.[5]

**Figure 6.2** Example of a fuel cycle including production of nuclear weapons



Uranium extraction can be achieved through a number of methods. Open-pit mining uses surface mining techniques to excavate the ore through blasting and drilling. The holes that are produced are often significantly larger than the ore deposits since the walls of the pit must be sloped to prevent collapse. Alternative processes, referred to as in situ leach mining, use acidic or alkaline mining solutions. This brings uranium to the surface in a dissolved state by passing the solution through the ore body via a series of bores or wells—the dissolved uranium is then ready for purification.

Once the ore is extracted, milling operations, that usually take place near the uranium mine, are used to extract the uranium from the ore. Uranium rock from open-pit mines will be crushed and ground into slurry, which is leached in sulphuric acid to allow the separation of uranium from the waste rock. The uranium is then recovered from the solution and precipitated in the form of uranium oxide ($U^{3}O^{8}$) concentrate, called 'yellowcake', that has a uranium concentration of 80 per cent. The yellowcake is then dried (and sometimes baked) before being loaded into 200-litre drums, which can then be sold or otherwise transferred. Any remaining crushed rock, known as 'tailings', is then disposed of separately.

## Uranium conversion

The yellowcake product is not directly ready for use in nuclear reactors on leaving the mill. Natural uranium only contains about 0.71 per cent of the fissile isotope uranium-235 ($^{235}U$), which is the isotope that is capable of undergoing and sustaining fission. Some nuclear reactors such as the British Magnox or Advanced Gas-cooled Reactors (AGRs), or heavy water reactors, do not require enriched uranium and can run on natural uranium, that is, uranium that is of the same isotopic ratio as found in nature. For use in these reactors, yellowcake needs to be converted to uranium dioxide ($UO^2$). Most power plants, however, require uranium that contains a higher concentration of $^{235}$U—typically between 3.5 and 5 per cent. For this process, the yellowcake is converted into uranium hexafluoride ($UF^6$), which forms as gas at relatively low temperatures.

The conversion of uranium oxide into hexafluoride may be achieved through either a 'dry' process, which is favoured in the US, or a 'wet' process that is used across the rest of the world. Refined yellowcake, which has had its impurities removed by nitric acid, is dried and mixed with hydrogen and nitrogen to form uranium trioxide ($UO^3$). In the dry process, $UO^3$ is reduced in a kiln by hydrogen to uranium dioxide, which is further reacted with hydrogen fluoride (HF) in another kiln, to form uranium tetrafluoride ($HF^4$). The tetrafluoride is then fed into a fluidised bed reactor with gaseous fluorine to produce $UF^6$. The wet process only differs from the dry process in that the impurities are removed through solvent extraction. The wet process involves making the tetrafluoride form uranium oxide through aqueous HF. The uranium hexafluoride product is then put into 14-tonne cylinders where it solidifies over a period of five days. The containers are then taken to an enrichment plant.[6]

## Uranium enrichment

As mentioned above, developing nuclear weapons or fuel for certain types of reactor requires access to quantities of $^{235}$U that are not available in nature. In most reactors, the amount of $^{235}$U is enriched to between 3.5 and 5 per cent: uranium enriched at this level is generally known as low enriched uranium (LEU).[7] In contrast, highly enriched uranium (HEU) is enriched to contain at least 20 per cent $^{235}$U and is used in fast neutron reactors and in naval reactors (uranium in naval reactors often contains at least 50 per cent $^{235}$U). While 20 per cent $^{235}$U

### **Box 6.10** Techniques for enriching uranium

There are four main types of enrichment process:

- **Gaseous diffusion** Diffusion exploits the weight differential of different uranium isotopes. Lighter molecules in a gas will move with a greater average velocity than heavier molecules. Uranium hexafluoride containing $^{235}$U and $^{238}$U is compressed and allowed to diffuse through a barrier or porous membrane. The lighter $^{235}$U molecules will travel faster than heavier $^{238}$U, meaning that the emerging gas will be slightly more enriched in uranium hexafluoride molecules containing $^{235}$U molecules.[8]
- **Gas centrifuge** This method uses centrifugal acceleration created in a cylinder rotating at very high speeds. Uranium hexafluoride is fed into a series of these rotating cylinders: the acceleration of rotation draws heavier $^{238}$U molecules toward the outside of the chamber while lighter $^{235}$U molecules remain in the centre. Standard centrifuge enrichment can be easily modified to produce HEU, and such modifications can be concealed.
- **Electromagnetic separation** Charged particles follow circular trajectories when passing through a uniform magnetic field. $^{235}$U and $^{238}$U isotopes have the same kinetic energy and electrical charge, but different masses. This means that they will have different trajectories (the heavier $^{238}$U have a larger diameter), which allow them to be separated and collected. The process is, however, extremely energy-intensive and expensive in comparison with alternative methods.[9]
- **Laser** A laser's ability to produce collimated light—involving parallel light rays—of a particular wavelength is used to excite $^{235}$U atoms to the point that they can be separated from $^{238}$U. Laser enrichment has been a focus of interest for some time, as it requires lower energy input and is therefore more affordable.[10]

is usually regarded as the minimum enrichment for nuclear weapons use, weapons-grade uranium tends to be enriched to over 90 per cent $^{235}$U.

Several enrichment processes have been developed (see Box 6.10), but only two have been used on a commercial scale—gaseous diffusion and gas centrifuge. Both of these processes exploit the mass difference between molecules of uranium hexafluoride containing $^{235}$U atoms and those that have heavier uranium isotopes, such as $^{238}$U. The enrichment process results in the production of two streams that contain different uranium isotopes. One stream contains the enriched product of higher concentrations of $^{235}$U, which will be used to make nuclear fuel or weapons material. The second stream contains lower concentrations of $^{235}$U, which is known as depleted uranium or 'tails'. Once enrichment is completed, the uranium hexafluoride containing higher amounts of $^{235}$U is converted to uranium dioxide (UO$^2$) in a powder form, where it can be shipped to a fabrication plant to be made into fuel or shipped out to the military for weapons purposes.

An enrichment plant's capacity is measured in terms of Separative Work Units (SWU). Simply stated, SWU stands for the effort required to separate $^{235}$U and $^{238}$U. The measurement indicates the amount of energy used relative to the amount of uranium processed, as well as the level to which it is enriched and the remainder is depleted. The unit is expressed in kilogram Separative Work Units, while the actual capacity of an enrichment plant is measured in tonnes SWU per year (tSW/a).[11]

## Fuel fabrication

Reactor fuel generally takes the form of ceramic pellets of pressed uranium dioxide (UO$^2$) fuel. The UO$^2$ is pressed into cylinders that are about the size of a fingernail, which are then sintered (baked) at a high temperature (over 1400°C). With a melting point of around 2800°C, ceramic pellets can operate at high temperatures. Moreover, ceramic has the added value of containing radioactivity in the reactor fuel. One uranium pellet contains approximately the same amount of energy as 800 kilograms of coal or 560 litres of oil.[12] Once sintered, the pellets are milled into shape and then loaded into metal tubes, to form fuel elements. These tubes also help to contain any radioactive gases that are given off by the pellets. The fuel elements are then collected together in bundles to form fuel assemblies that are carefully designed to allow the transfer of heat to the cooling water that surrounds them during reactor operations.

## Nuclear reactors

Nuclear reactors can be grouped into two basic categories: thermal reactors and fast reactors. Thermal reactors moderate the speed of neutrons, to slow them until they are more likely to cause nuclear fission in $^{235}$U. Typically, moderators include water, heavy water or graphite. This is achieved because the moderators absorb some of the neutron's kinetic energy, slowing them down to the thermal energy of the moderator nuclei. This group of reactors includes most of the power reactors in current use.[13]

In fast reactors, on the other hand, the neutrons are not noticeably slowed down before causing fission in other nuclei. These reactors do not rely on moderators but, instead, use fuel that is rich in fissile material. The coolant is a material that neither absorbs neutrons nor interferes with their speed—usually molten sodium or a gas such as helium.[14]

When used for commercial purposes, nuclear power plant operations are similar to their fossil-fuelled counterparts: the reactor core, the portion of the reactor that contains the nuclear fuel, heats water to produce steam at high temperatures and pressures, which drive turbines, which then turn generators to produce electricity. Nuclear reactors generate their heat through fission of the $^{235}$U contained in the fuel assemblies. However, through neutron capture by $^{238}$U atoms, plutonium isotopes also build-up in the fuel and contribute to the overall energy output.

Plutonium is an extremely rare element that only occurs naturally in minute quantities. It is essentially a man-made element that is produced through nuclear fission. The isotopic composition of plutonium is affected by the reactor burnup—the degree to which the reactor fuel is exposed to neutrons over a period of time. Short exposures, for example, produce greater quantities of plutonium-239 ($^{239}$Pu), which is the most desirable isotope for nuclear weapons as it can sustain a fission chain reaction. However, longer exposure to neutrons in the reactor core leads to a larger build up of the higher plutonium isotopes ($^{240}$Pu, $^{241}$Pu and $^{242}$Pu). The isotope $^{241}$Pu

### **Box 6.11** Different types of nuclear reactor

**Thermal reactors:**

- **Light Water Reactors** By far the most numerous reactors in the world, light water reactors (LWR) use water as their moderator. There tend to be two main types: pressurised water reactors (PWR) and boiling water reactors (BWR). The PWR heats water under high pressure to keep it below the boiling point within the reactor core. The water is pumped from the core through steam generators that contain a secondary circuit where the water is allowed to boil to form steam and to drive turbines. In the BWR, coolant water within the reactor core is allowed to boil, and the resultant steam is used to drive the turbines directly.[15]
- **Heavy Water Reactors** Heavy water, or deuterium oxide, is used as a moderator in some reactors as it absorbs fewer neutrons than light water. As such, heavy water reactors like the CANDU pressurised heavy water reactor (PHWR) can use natural uranium fuel. The heavy water serves as both coolant and moderator in a similar way to the light water in PWRs and BWRs. The fuel is contained in pressure tubes within the reactor core itself.

  CANDU reactors can be refuelled while still in operation. This feature could be used to move fuel through the reactor at a faster rate. This would mean that the fuel's exposure to neutrons is limited and so it would produce larger concentrations of 239Pu.[16]
- **Gas-cooled reactors** Predominantly found in the United Kingdom, using carbon dioxide or helium as a coolant, these reactors can achieve a higher thermal efficiency (40 per cent or more) compared to water-cooled reactors (33-34 per cent), as the coolant can be heated to higher temperatures than water.

There are two types of gas-cooled reactor. Magnox reactors (named after the magnesium alloy that clads their fuel elements) use graphite as a moderator to slow down neutrons. These reactors use natural uranium fuel elements that are inserted into vertical channels in the graphite core. The other type, developed by the United Kingdom, is known as the advanced gas-cooled reactors (AGRs), which use uranium that has been slightly enriched (usually to 2-3 per cent 235U).[17]

is fissile, but has a short half-life of 14 years (it decays into americium-241), which emits intense X-rays and gamma rays and heat, which needs to be dispelled. $^{238}$Pu, $^{240}$Pu and $^{242}$Pu are also undesirable as they spontaneously fission at a higher rate than $^{239}$Pu, producing higher energy neutrons and a lot of heat. The neutrons emitted in this fission process increase the likelihood that the chain reaction in a nuclear explosive device will begin before full compression of the plutonium has been achieved—causing pre-detonation.

## Storage

In civilian reactors, fuel assemblies are removed from the reactor core after 3-6 years of operation. However, when producing weapons-grade plutonium, fuel assemblies may only remain in the reactor core for less than a year. In either case, the level of radioactivity in the spent fuel is very high as it contains radioactive fission products and radioactive nuclei formed by neutron capture. In addition, the spent fuel is thermally hot as the energy released from radioactive decay appears as heat. As such, the first step for managing spent reactor fuel is to cool it for a desired period of time. Once removed from the reactor, the spent fuel assemblies are stored under water to let them cool. This also serves as a shield against radiation.

The duration of this initial cooling period depends on the final purpose for the spent fuel. If the accumulated plutonium is to contribute to a nuclear weapons programme, then spent fuel assemblies will undergo shorter cooling periods than those coming from civilian reactors. In many countries, spent civilian fuel will be stored underwater for 10-20 years before progressing on to either reprocessing or long-term storage.

Both the heat and radioactivity of the spent fuel decrease over time. After 40 years in storage, the spent fuel's radioactivity will be about a thousand times lower than when it was initially removed from the reactor.

## Spent fuel reprocessing

This activity involves chemical treatment of spent fuel to separate and potentially to isolate one or more elements (typically uranium or plutonium) from unwanted radioactive by-products. In reprocessing, spent fuel is dissolved in acid; the plutonium and uranium are chemically extracted so that they can be used in either new fuel or, in the case of plutonium, in nuclear weapons. If the goal is to produce weapons-grade plutonium the process is sometimes referred to as plutonium separation, as the plutonium is separated from all the other radioactive materials, including fission fragments and other impurities, which must be dealt with separately.[18]

The most commonly used method for reprocessing is the hydrometallurgical plutonium-uranium extraction (PUREX) process. The first step in this process involves removing the spent fuel from its cladding by either mechanical or chemical means. The uranium and plutonium content is then separated from the rest of the spent fuel by dissolving it in boiling nitric acid.[19] The uranium and plutonium nitrates are then subjected to solvent extraction.

As with freshly mined uranium, the uranium recovered by reprocessing can be converted to uranium hexafluoride and re-enriched, returning to the fuel cycle as 'recovered uranium'. The plutonium can be mixed with uranium and used to fabricate mixed oxide fuel (MOX) for nuclear reactors. The high-level waste—the highly radioactive materials produced as a by-product of the irradiation process—can be vitrified (converted into glass) to be disposed of in a high-level waste disposal facility. Approximately one third of the fuel discharged from nuclear reactors is reprocessed.[20]

## 6.2.2 Building a nuclear fuel cycle model

The process for creating a nuclear fuel cycle model has three stages. These stages progress from developing a broad concept to detailed specifics, and then on to practical data that can be used in simulations. This section expands on each stage in this process.

It is worth highlighting here that the methodology for creating a nuclear fuel cycle model operates in parallel with the creation of a scenario. Although the two processes have been explained separately for reasons of practicality, the model and the scenario can be understood as two parts of the same product. It is therefore necessary for the two processes to be developed alongside one another to ensure that the information provided for the simulation tasks is reliable, realistic and internally consistent.

For the purpose of developing a model, specifically, it is advised to follow an end-focused approach. First, establish a general picture of the modelled state's nuclear fuel cycle at the time of disarmament, and then chart the history of the state's nuclear activities with the aim of developing a model of a state with that nuclear profile. This approach provides a boundary for developing the model, prevents it from becoming too complex, limits inaccuracies and helps to prevent the accumulation of superfluous information.

### Stage 1: basic parameters

In this stage, a suitable profile must be devised for the country to serve as a base on which the fuel cycle model and the main features of the state's nuclear programme will be developed. Initially, modellers must decide the main features and general profile of the nuclear fuel cycle to be modelled, including its general size, complexity and sophistication. This forms the basis for the model's nuclear fuel cycle profile.

Guided by this decision, the next step involves carrying out case study research into similar historical nuclear weapon programmes that relate to that type of state. This helps to establish a set of real-life examples to inform the construction of the final model and dictates the types of facilities and technologies that are appropriate for that country. For example, if the aim is to create a small nascent nuclear weapon programme that has undertaken a heavily clandestine approach to weapons acquisition, then research could focus on the nuclear weapons programmes conducted by Argentina, Iraq, Libya, DPRK, South Africa and Sweden. Within many of these case studies, previously civilian driven facilities were converted for military purposes in order to avoid raising suspicion in the international community. It therefore follows that a modelled clandestine weapons programme should avoid activities that would draw attention to its aims—for example, it might not make sense for a state to suddenly import large stocks of $U^3O^8$ or to construct advanced enrichment facilities.

As mentioned above, this process mirrors the creation of a general country profile to inform the development of a disarmament scenario, as described in Section 6.1.1.

From here, it is possible to draw-up an initial image of the state's nuclear fuel cycle and the constitutive parts that are required to produce its nuclear arsenal. For example, a decision can be made as to whether or not the state has developed independent fuel cycles for civilian and military purposes, or whether they share facilities at different times during the state's development. The selected option will indicate how the modelled state will behave and the types of technologies it will use. This is further dependent on the modelled state's access to nuclear source material and whether it must import uranium or has an indigenous mining capacity.

## Stage 2: a timeline of nuclear development

In this stage, key questions concerning the modelled state's history and the general features of its nuclear weapons programme are answered in order to guide the construction of a detailed timeline. This involves deciding on the final number of weapons that will make up the state's nuclear arsenal, the arsenal's diversity (whether it will be constituted by one or more weapon classes) and composition (whether the weapon cores are made of uranium, plutonium or a mixture of the two).

Once the modelled state has been given a suitable profile, a final number of nuclear weapons, and a fissile material demand, it becomes possible to add greater detail to the background history for its technical development.

The first step involves projecting backwards the number of years required to achieve the target number of weapons and the quantities of material needed for the simulation. For example, if the present date is 2015, and the modelled state is a sophisticated nuclear weapons programme with many thousands of weapons, then it will require a longer timeline than a DPRK-like state with a smaller nuclear arsenal, in order to create the requisite material and to test and stockpile its weapons. In this case, the state may need a history of over 50 years, perhaps even 60-70 years. The starting year could then be expressed as T-60 or T-70 respectively, where T stands for *time* and the number represents the number of years leading up to T0, the year when the state decides to disarm.

To ensure that each facility in the model's timeline is credible, in terms of historical accuracy for the technologies it uses and its overall coherence, the following needs to be considered carefully:

- How many years would it take to construct a given facility?
- How long will it take for a quantity of material to pass through the facility?

The process of devising the timeline needs to focus on the end-purpose for the model (the final number of nuclear weapons and quantities of fissile material) in order to identify a suitable start-up date for each facility and to give it time to complete its operations.

Each facility in the timeline must be equipped with appropriate technologies for the period that it is operating. There is little value in having a model that includes present day technologies that are inappropriate for earlier decades.

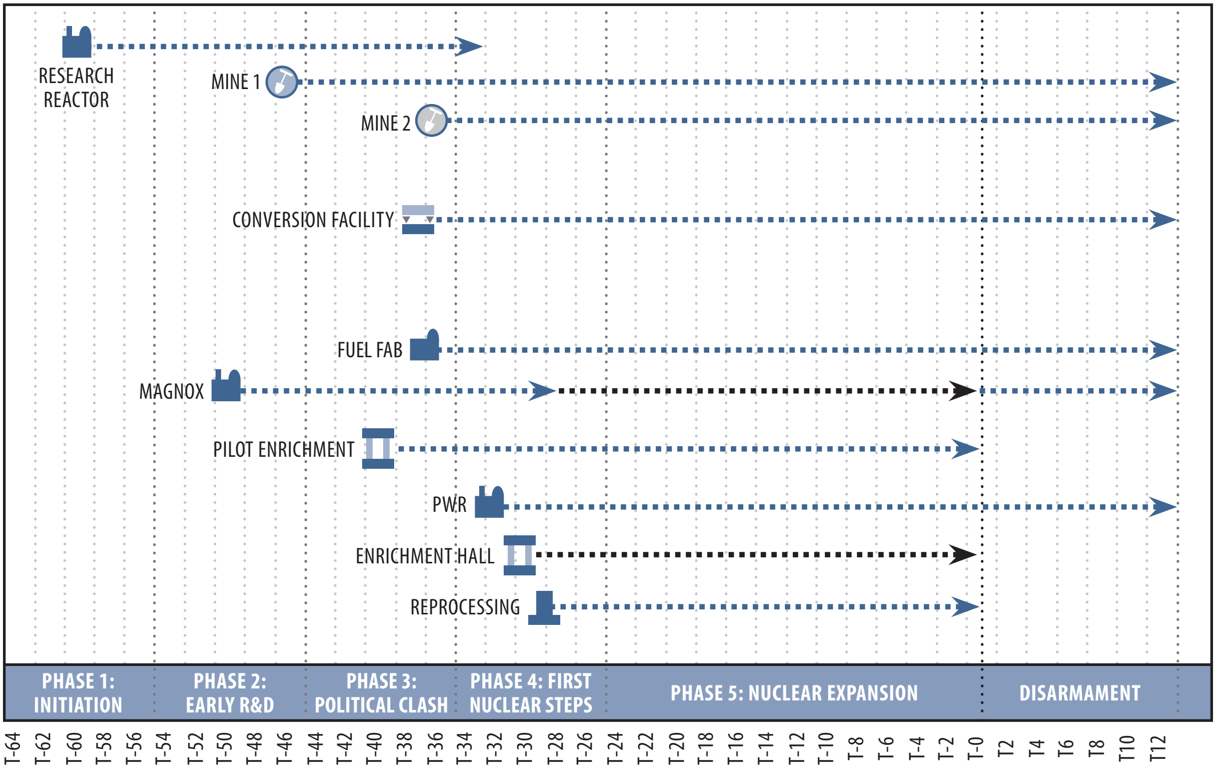
In addition, each facility in the fuel cycle should be given an individual profile that provides details on its specific operating conditions and properties. Box 6.12 provides an indicative list of questions to consider when developing an individual facility profile.

The answers to these questions are fundamental for generating data for the model and for plotting a timeline for the state's development of nuclear weapons. This timeline draws together all the features of the above process, and can project them as a visual flow diagram for the modelled state's fuel cycle. An example can be seen in Figure 6.3, which shows the timeline for a model state called Example Country 2, which is based on a fuel cycle that is not dissimilar to the one of DPRK. The diagram is broken down into specific decades that represent the major political events taking place in Example Country 2, on which the start-up dates for

### **Box 6.12** Facility profile specifications

- When does the facility come online and when does it cease operations?
- What is the facility's annual capacity?
- What is the annual material feed requirement?
- If the state is developing enrichment capabilities, which centrifuge design does it use and how many centrifuges does the plant house?
- With respect to reactors, what type of reactor is being used? Is it optimised for civilian or military purposes?
- What is the quantity of fuel needed for each core?
- How long does fuel stay in the reactor and what is the maximum burnup for each irradiation cycle?
- How long does it take to refuel the reactor?
- What type of reprocessing technique does the state use?
- How does it dispose of its waste material? Does it recycle spent fuel from its civilian programmes?

**Figure 6.3** An example of a timeline diagram for a nuclear fuel cycle model[21]



each fuel cycle component is plotted. The arrows leading from each facility span the years that the facility is in operation (black arrows indicate military use).

The timeline should account for the fact that processes in nuclear facilities can take different periods of time to complete and for the material to move onto the next site. Initially this detail may appear excessive, but it helps to prevent the model from becoming unrealistic. For instance, if the state developed its own nuclear facilities and utilised indigenous uranium ore supplies, then the model will require mines and milling facilities. The timeline will need to take into account the time needed to develop these facilities and to exploit the uranium deposits so that sufficient quantities of uranium has accumulated for the conversion process—the time this takes is dependent on the modelled state's mining profile and the richness of its deposits.

If the state does not have access to uranium mines then it may import stocks of yellowcake to feed its nuclear programme, which could shorten the timeline by a few years. If so, then the first facility to enter into operation could be a conversion plant for producing uranium hexafluoride, followed by an enrichment plant (if the state is utilising LEU fuel) and then a fabrication plant. This process could take a year or two, depending on the size of the facility, to complete before fuel is ready for the nuclear reactor, especially if there is a large core. It may be simpler for the modeller to choose the start-up date for the reactors before any other fuel cycle facilities. This enables the modeller to ensure the fabrication plants have generated sufficient fuel in advance of the reactor start-up date.

### Stage 3: data generation

Once each facility has been plotted on the timeline, the next stage involves generating data on a year-by-year basis for all material processes taking place in the fuel cycle. The details for this stage are explained in Section 6.2.4 and Section 6.2.5.

## 6.2.3 Software solutions

Section 6.2.1 provided an overview of the various stages of the nuclear fuel cycle as well as the types of chemical and mechanical processes involved. In order to create nuclear fuel cycle models for a range of possible nuclear programmes of varying sizes and configurations, similar real-world countries will need to be examined. This helps to ascertain the parameters and assumptions underlying the development timeline and facilities for a given model, as well as the overall sophistication of its nuclear programme. The information obtained through this process ensures that each modelled country developed its nuclear programmes at an appropriate rate and with technology appropriate to the time. In addition, it is necessary to have in-depth knowledge of how to calculate the production and movement of nuclear material in each stage of the fuel cycle, and to represent it as quantitative data.

This task could be a time consuming activity, but helpful tools are available. While a significant amount of information can be obtained through a combination of open-source research and expert analysis and commentary, there are also a number of analytical software programmes that have been developed to form nuclear fuel cycle simulators or to simulate specific aspects of the fuel cycle process. This section discusses a selection of these software programmes and how they might be used for modelling purposes.

### Fuel cycle simulators

Nuclear fuel cycle simulators are software tools that explore the effects of alternative nuclear fuel cycle configurations. They track the flow of materials through the nuclear fuel cycle for all facilities and provide quantitative data for processes such as mining, milling, enrichment, fuel fabrication, irradiation in a reactor and chemical separation. Using data on the flow of nuclear materials and information about facility operating histories, various characteristics and measurements can be assessed for different fuel cycle designs.

To date, a variety of useful tools have been developed to explore different nuclear fuel cycle configurations and options. These include CAFCA, COSI, Cyclus, DANESS, NFCSim, NUWASTE and VISION.[22, 23] These tools either rely on models of facility operating conditions that have been created and validated using measurements from real world examples, or on simplified systems models that perform faster calculations, but lack precision. While the former category of software provides greater accuracy on the physical processes involved in different facilities and operations, these are complicated tools that require a high level of expertise. The latter category, on the other hand, sacrifice accuracy for computational speed but are easier to use.

These software programmes are used across the world to explore a range of issues relating to economics, sustainability, or non-proliferation issues and can be used to inform decision-making on research, development and deployment for future fuel cycle facilities. They are, therefore, not optimised to investigate material requirements and flows for nuclear weapons programmes. Moreover, many of the existing software programmes that do provide detailed modelling solutions for nuclear fuel cycles are not readily available for use outside of governments or the organisations that developed them, and those that are tend to require a level of technical knowledge that makes them virtually impracticable for many users.

An ideal software programme for modelling different nuclear weapons programmes would provide quantitative data for material flows and technical processes (especially uranium enrichment, plutonium production and any secondary chemicals) for each step of the nuclear fuel cycle. Given the sensitivity of much of the information associated with nuclear weapons programmes, the programme could be developed as a simplified system to provide estimated but appropriate figures for various processes.

Such a software programme would be most effective if it utilised an interactive graphical user interface that allowed for easy fuel cycle construction and clear presentation of material quantities flowing between facilities. In order to be of value, each facility would require multiple options for the various technologies or techniques that they employ and allow users to select the metric that is most suitable for the modelling purposes. For example, the programme could provide a modelled version of different reactor designs based on real world examples such as PWRs, BWRs or Magnox reactors that enable users to vary the burnup or the isotopic composition of the reactor fuel. In addition, the programme could include enrichment facilities with options for simulating different types of separating techniques (for example, gaseous diffusion, gas centrifuge or even laser separation) as well as data for different types and numbers of enrichment techniques or centrifuges, such as the different URENCO designs.[24] Finally, the software programme could be designed to enable the user to measure material flows over various periods of time—days, months and years. This would provide a greater ability to estimate how much material can be produced in a given facility over various time scales.

## Modelling nuclear reactors: ORIGEN-ARP and reactor physics

While a number of potentially useful analysis programmes have been developed for modelling entire fuel cycle systems, there are also options available for simulating specific aspects of the fuel cycle in more detail. One of these tools is the commonly used ORIGEN-ARP software programme that has been created as part of the SCALE (Standardized Computer Analysis for Licensing Evaluation) system, developed and maintained by Oak Ridge National Laboratory in the US.[25]

ORIGEN-ARP provides users with accurate and detailed data on a number of reactor types but not on other parts of the fuel cycle, such as enrichment or conversion. It utilises a standardised method for analysing isotopic generation and decay for spent fuel, fissile material and other fission products. It provide comprehensive, verified and validated data on reactor physics and spent fuel characterisation to be used for making predictions about spent-fuel composition and reactor performance.[26] By experimenting with variables such as the burnup and fuel composition, users can simulate reactor operations for the models discussed in this section, for either civilian or military programmes.

For example, modellers can choose from a list of nuclear reactor types that match the technological capabilities of the state being modelled. As mentioned in Section 6.2.1, an emerging nuclear weapon state may not have access to enriched uranium, so it may choose to utilise natural uranium-fuelled reactors similar to the Magnox reactors that were developed by the United Kingdom, or North Korea's Yongbyon reactor. Alternatively, the model may need to supply data for a commercial nuclear power programme. Light water reactors are by far the most numerous form of commercial reactors in the world today, and so the model may want to simulate the activities of a PWR. ORIGEN-ARP contains cross-section libraries for a variety of reactor designs that include a Magnox reactor based on Calder Hall in the United Kingdom, and several light water reactor designs such as the Russian VVER-440 and VVER-1000.[27]

If the intended purpose is to investigate plutonium production for nuclear weapons, then users can vary the burnup. As discussed in Section 6.2.1, burnup is the extent to which reactor fuel has been exposed to neutrons. It is usually defined in terms of the number of megawatt days of energy produced per tonne of fuel (MWd/t). The preferable conditions for producing weapons-grade plutonium require the uranium fuel to have a lower exposure to neutrons than that reached in commercial power reactors. This is because fuel that reaches a higher burnup contains greater concentrations of plutonium isotopes that are less suitable for nuclear weapons.

For example, in commercial pressurised water reactors, the final burnup can range between 23,000 MWd/t of uranium in older assemblies to 43,000 MWd/t or more in modern ones. This is principally due to economic factors: it would be far more expensive for commercial power reactors to irradiate their fuel for a period of a few months before replacing it. Instead, commercial reactor fuel can stay in the core for three to four years at a time. Reactors used for producing weapons-grade plutonium, by contrast, reach a burnup that is a fraction of this. Lower burnup can be achieved by irradiating reactor fuel for short periods of time, maybe even a matter of weeks, before it is discharged.[28] The final discharge burnup is usually below 1000 MWd/t. For example, the North Korean Magnox reactor at Yongbyon, operated to a final burnup of less than 700 MWd/t.[29]

Once the sample of fuel has undergone the required irradiation and decay cycles, the user can analyse the fuel's isotopic content and the quantities of plutonium that have built up in it. Data for the uranium sample can then be extrapolated to provide figures for the quantities of plutonium and other actinides for the whole reactor core load.

The information provided by ORIGEN-ARP is ideal for modelling material flows for nuclear reactors and offers great detail for the purpose of having precise data on plutonium production in a given reactor set-up. One limitation of ORIGEN-ARP is that it cannot model research reactors, but the level of detail it provides for other reactor types is invaluable for the modelling process. By combining the specific and detailed data generated by ORIGEN-ARP with other fuel cycle simulator programmes mentioned in this section, researchers could create comprehensive models for a diverse range of nuclear fuel cycle configurations. The following subsections provide more detail on how to model civilian and military programmes that can be used for investigating verification requirements under varying disarmament scenarios.

### 6.2.4 Flows of civilian fissile material

Section 6.2.2 discussed the overall process for creating nuclear fuel cycle models. As explained, this three-stage process starts with establishing a broad profile of the modelled state, and then elaborating specific details concerning its nuclear arsenal, its historical fuel cycle development over a set period of time and finally data on its material flows on a year-by-year basis.

In many existing nuclear weapons states the same nuclear facilities operate for military and civilian purposes at alternating times. It is therefore necessary for the model to include full records for material production in a nuclear weapon state's civilian programmes—as well as in its military programmes (as discussed in Section 6.2.5)—to be able to determine the state's complete fissile material production history and enable simulation participants to investigate ways to verify declared histories.

This section describes the methodology for generating data for a civilian nuclear fuel cycle model. Specifically, it focuses on how to generate data for fissile material production and how to capture this information. The emphasis here is on selecting data that can be used for investigating verification challenges in a disarmament simulation. Section 6.2.5 provides greater detail on the final stage of the modelling process: modelling nuclear weapons programmes and converting fissile material into weapons components.

## Essential information and desirable information

A number of prerequisites need to be taken into account when generating data for nuclear fuel cycle models. Principally, there should be a clear understanding of the model's purpose and what type of information is needed to achieve it. As highlighted in Section 6.2.2, the process for building a model should be focused on its end-use; the same is true for data collection. Without a clear understanding of the model's final purpose, there is a risk of overloading it with superfluous information. For a model that is focused on providing a foundation for conducting future disarmament simulations, essential information might include:

- The quantities of nuclear material moving between facilities, in storage or held-up in processes in any given year;
- Details concerning material composition (isotopic content); and
- Individual facility operating specifications for each year of operation.

This information, once complete, can be drawn on when simulating verification activities that focus on the origin and production of fissile material. It is, therefore, necessary for each facility in the model to provide a realistic representation of a real-world counterpart, and so the quantities of material created by each facility and located in the whole model need to be consistent with this expectation.

Generally speaking, finding information to help construct a realistic model fuel cycle and timeline should be relatively straightforward. Many features of the civilian fuel cycle are well documented in open-source literature, while, as discussed in Section 6.2.3, specific software packages exist that can deliver material production data for various fuel cycle configurations. However, although there exists an abundance of information on civilian facilities, the same cannot be said for military programmes and the details surrounding weapons production. Information on these processes is naturally politically sensitive and potentially proliferative in nature. As such, the process of abstracting weapons-usable fissile material from the modelled fuel cycles and placing it into a modelled nuclear warhead is laden with challenges.

To develop a comprehensive model of a notional nuclear weapon state therefore, it is necessary to navigate between two extremes: on the one hand sifting through and selecting from a glut of information on the nuclear fuel cycle, and, on the other, contending with the paucity of information on weapons production and their material requirements (more on this in the following section).

When it comes to modelling civilian fuel cycle activities, parsimony should be the guiding principle: a model derives its power from its ability to represent a process or phenomenon simply. It is therefore crucial to make key decisions on what information is essential to the model's purpose and what is additional or just 'nice to have'.

For example, in addition to recording quantities of fissile material for all facilities at any time in the modelled timeline, the model should include the individual operating specifications for each facility on a year-by-year basis. This information is useful for two reasons. First, in simulation exercises, participants may rely on these details to address any questions that arise over the accuracy of a given set of accounts for specific facilities during mock inspection activities. For example, if the disarming state supplies reactor records that have gaps in them (as stipulated by the disarmament scenario: see Section 6.1), then the inspection team can use a reactor's operating data (for example, its burnup and the reactor's core capacity), to estimate the amount of plutonium that may have been created in a given year. Second, by recording the specifications for each facility, the model can easily be replicated. This will help to add credibility to the models and to validate and replicate the quantities of material they contain.

There are, however, other types of information that could provide additional detail, but are not essential and could become burdensome. For instance, when modelling reactors, the primary aim is to account for plutonium production, but the remaining quantities of uranium in irradiated fuel or other fission products (such as quantities of americium-241) could also be recorded. An analysis of these isotopes could be used to investigate any discrepancies in mock records provided by simulation participants representing the disarming state. This could help add an additional layer of realism to simulations, especially if the disarming state was trying to retain a nuclear weapons capability through a clandestine programme.

While this type of information is clearly useful, recording it on a year-by-year basis for a model fuel cycle of over 60 years can be time consuming. Moreover, simulations are not necessarily contingent on this data being stored in the model. Instead, it can be created ad hoc, by using the recorded facility specifications that are recorded within the reactor facility sheets (more on this below).

## Displaying fuel cycle information

The process for populating the model with data for fissile material production and material flows can be seen as a continuation of the timeline activity described in Section 6.2.2. After establishing the timeline and individual histories for each facility in the fuel cycle and mapping out their operating specifications, additional research can be conducted into the material production processes involved in each stage of the fuel cycle.

This data forms the heart of the model: it provides details on the capacity of each facility in the fuel cycle model and indicates the quantities and types of material that enter, are processed and leave the facility on an annual basis. Once this data is compiled, the model will contain a full set of accounts that record the specific quantities of source and fissile material flowing between, stored in or undergoing processes in every facility in each year of the modelled state's nuclear fuel cycle history.

Depending on the profile of the state in question, there are multiple options available for generating this data. It is not difficult to obtain information on the annual production capacities and operating specification of most fuel cycle facilities. There is an abundance of open-access resources and textbooks available that provide detailed descriptions and technical instruction on each stage of the nuclear fuel cycle and their operating conditions, as well as calculations for estimating material production.[30]

Alternatively, as discussed in Section 6.2.3, software programmes can be employed to calculate material flows for all or part of the civilian fuel cycle. ORIGEN-ARP, for example, can provide precise data for plutonium production in reactor fuel for both civilian and military reactors. Once a reactor type has been chosen, users can alter specific variables (for example, the neutron flux and the length of time that the fuel stays within the reactor) in order to simulate reactor operations of their choice. For reactors involved in civilian operations, it is just a case of identifying the optimal burnup for the fuel that is appropriate for the type of reactor and its core size, so that it can maximise power generation.

The data for material flows and production can then be contained in sets of datasheets that represent every facility in the modelled state's fuel cycle, both in civilian and military use. These sheets are used to record quantitative data: operating conditions and the yearly mass flows for each facility in the modelled fuel cycle. Box 6.13 shows the contents of such data sheets.

### **Box 6.13** Facility sheet information

- Facility type and its years of operation (including start up times, time spent refuelling or shut down and the year when the facility ceases operations)
- The facility's operating conditions, properties and capacities (e.g. reactor burnup, maximum core load, thermal power or centrifuge SWU);
- Quantities of material before, during and after a given process for each year;
- Quantities of a specific isotope of interest ($^{235}$U and $^{239}$Pu) before, during and after a given process for each year;
- Cumulative material in a facility before, during and after a given process;
- Quantities of material being dispatched from a facility for each year;
- Shut-down or refuelling periods;
- Loss factors for specific processes (e.g. material lost during conversion of $U^3O^8$ to $UF^6$); and,
- Tails or waste quantities.

**Table 6.1** Example of a facility sheet for a civilian PWR nuclear reactor[31]

| Facility input | | Facility operating process | | | | | | Facility output | |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Feed mass (kg)** | **Burnup (MWd/th)** | **U in fuel (kg)** | **$^{235}$U in fuel (kg)** | **Pu content in fuel (kg)** | **$^{239}$Pu in Fuel (kg)** | **$^{239}$Pu% in fuel** | **Dispatched U (kg)** | **Dispatched Pu (kg)** |
| T-40 | 80,000 | 0 | 80,000 | 2600 | 0 | 0 | 0% | 0 | 0 |
| T-39 | 0 | 18500 | 77840.75 | 1300 | 586.22 | 413.04 | 70% | 0 | 0 |
| T-38 | 0 | 27,000 | 76972.16 | 928 | 745.56 | 467.68 | 63% | 0 | 0 |
| T-37 | 0 | 0 | 0 | 0 | 0 | 0 | 0% | 76972.16 | 745.56 |

**Table 6.2** Example of facility sheet for a civilian enrichment hall using 5,000 URENCO G2s

| Facility input | | | | | Facility operating process | | | | | | Facility output | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **UF$^6$ feed (kg)** | **$^{235}$U%** | **$^{235}$U Effective kg** | **SWU** | **Product UF$^6$ (kg)** | **Product $^{235}$U%** | **Product $^{235}$U Effective kg** | **Tails (kg)** | **Tails $^{235}$U%** | **Tails Effective kg** | **Product cumulative (kg)** | **Product dispatched (kg)** |
| T-40 | 44047.82 | 0.71 | 312.74 | 23500 | 5953.46 | 3.03% | 180.39 | 27082.4 | 0.2% | 54.16 | 5953.46 | 0 |
| T-39 | 44047.82 | 0.71 | 312.74 | 23500 | 5953.46 | 3.03% | 180.39 | 27082.4 | 0.2% | 54.16 | 11906.92 | 0 |

Each facility sheet is divided into three phases: an input, operating process and output phases for every year in the model's fictional timeline. If the modelled state has a development history of 70 years, there will be an equal number of rows on the sheet to account for each one. The phases are then subdivided into columns that contain space for recording data on specific processes and the type and quantities of material involved in each (all measured in kilograms) (see Tables 6.1 and 6.2).

Entering data for fuel cycle activities is relatively straightforward, especially for purely civilian fuel cycles. In this situation, there is no end product to work toward, as facilities are not contributing to the weapons programme. Such facilities will often run for decades at a time and will continue to operate beyond T0, when the state has agreed to disarm. However, the situation becomes more complicated when modelling military programmes, especially where fuel cycle facilities are utilised for both civilian and military purposes at different times. This is further explored in the next section.

## 6.2.5 Flows of military fissile material

The process of modelling military facilities, fissile material production and nuclear weapons arsenals is more complicated than civilian modelling. While there is an abundance of open-access resources on the civilian fuel cycle, there are far fewer available for military counterparts. This is not surprising, given that most details about nuclear weapons and their designs are officially classified. However, that is not to say that an investigation into the intricate processes, technologies and features of nuclear weapons will not yield results. There are many unclassified publications available that provide technical information on historical nuclear weapons programmes and the weapons themselves.[32] Speculations on warhead composition, pit formation, non-nuclear component manufacturing and weapons design have also been published online by many individuals who are not associated with any formal nuclear weapons programmes or complexes.

Although these resources do not provide comprehensive step-by-step instructions for building nuclear weapons, they nevertheless raise important questions for the modelling process and for arms control purposes in general. First, when modelling a military fuel cycle and nuclear arsenal, what information is needed to satisfy the requirement for accuracy and realism? How accurate does this information need to be, and how should it be gathered and stored? If specific information is classified and unobtainable, is there a way to generate meaningful estimations that are still useful? Second, how can sensitive information be gathered and used without posing a challenge to non-proliferation norms and international security? This section discusses these questions in more detail. The first part examines the issues associated with data collection with respect to gathering sensitive and potentially proliferative information, while the second part examines how to produce model data for fissile material that will be used in nuclear weapons.

## Data accuracy, security and usability

As with the model as a whole, the process of generating data on fissile material production for nuclear weapons is driven by the intended end-purpose. Section 6.2.2 noted that Stage 2 of the modelling process involved answering key questions concerning the overall fissile material demand for the final modelled nuclear arsenal. Decisions need to be made as to the size, diversity and composition of the modelled weapons stockpile as well as the date for any nuclear test explosions and the quantity of fissile material consumed in each one.

These are the essential interests for a model looking to account for fissile material in a nuclear weapons programme. However, there are other details concerning a nuclear arsenal that could be recorded. For example, the model could include information on the weapons specific design, the weapons assembly, life cycle and the precise composition and shape of the fissile component (that is, the warhead's pit). If the modelled arsenal includes more sophisticated explosives such as those in thermonuclear weapons, there could be benefit in accounting for the secondary stage explosives and the production, or importation into the state, of tritium and deuterium gas or lithium-deuteride.

Every feature of the above is highly classified and proliferative in nature, but is the subject of generic discussion, analysis and speculation in many open-access resources available online. If a decision is made to include these details in the model, disparate information will have to be gathered from a wide range of sources. However, this process raises several problems. First, the research process can take up considerable time and resources. Second, given the sensitive nature of the content, there are ethical considerations that must be addressed when collecting and collating information that, together, could be considered potentially proliferative, especially if published and circulated to wider audiences. This, in turn, raises questions about regulating dual-use and potentially proliferative information and determining who has responsibility for limiting its distribution. Third, in many instances the available information will only provide a partial and incomplete picture. Corroborating this information is also a significant challenge, as governmental departments and other official sources are highly unlikely to confirm whether or not it is correct, since that would potentially reveal classified information or even provide unwitting assistance in determining precisely what information is proliferative.

Verifying and validating assumptions made in the model on classified and sensitive matters is, in many respects, an insurmountable challenge. One method for circumventing this is to rely on appropriate approximations that are reasonable and respect the model's internal consistency. For example, the IAEA's definition of a 'significant quantity' could be used as a standard for the quantities of fissile material used in modelled nuclear weapon.[33] If the modelled state has had an expansive nuclear history with multiple generations of weapons, different weapons classes and many explosive tests, then the model could use larger quantities of a given fissile material for earlier weapon generations and classes, and then gradually reduce this amount (this assumes that subsequent weapons tests and weapons classes become more efficient over time and require less material).

Another aspect of the military programme that is heavily classified is the weapon manufacturing process within the weapons complex. Not only are details about the weapons classified, but also the technical and mechanical processes involved in assembling them. One way to model this process is to treat the nuclear weapons complex as a 'black box' where specific quantities of material enter the facility and undergo a series of unspecified processes that produce a final output product—a nuclear weapon with a pit consisting of an approximated quantity of fissile material. In this case, researchers can assume that the production process will result in a degree of material loss as the fissile material is shaped and machined to form the pit. It is therefore possible to apply a standard loss fraction for this process and to record the estimated material loss in the nuclear weapons complex facility sheet for each year of operation.

This information may not be representative of the actual amount of fissile material that is lost during the weapons manufacturing process, but it can still be used to research verification solutions. For example, this information could be used in research or simulations focusing on the verification of declared quantities of fissile material being released from nuclear weapons or contained in a weapons facility. Estimations may sacrifice accuracy, but are, nevertheless, useful for modelling purposes as they let researchers bypass details that are otherwise sensitive, heavily classified or completely unknown. As long as the information remains internally consistent, the modelled data can still provide a platform for testing and assessing existing verification technologies and procedures.

## Fissile material production data

One of the challenges in creating a realistic model of a nuclear fuel cycle is establishing a plausible timeline of facility operations and material transfers. This should allow each facility to operate as intended, receiving and producing the required quantities of material at the appropriate intervals. If the supply and production of fissile material is not considered carefully, the modelling process might reach a point where some facilities do not receive enough material at the intended time. This could impact on the model's timeline, slowing down weapons production, which may mean that the model does not contain sufficient numbers of weapons. It could also happen that some facilities produce more than is required, and materials without a direct use or application start to accumulate. It must be noted that these types of inefficiencies can and do take place in real fuel cycles. As such, it may be appropriate to introduce them in a model voluntarily.

If, however, they occur unintentionally (in other words, there is a mistake in the model) there are a number of ways to deal with them. One method involves increasing the state's overall capacity to produce material in order to satisfy demand, either including additional facilities or increasing the capacity of individual facilities. Alternatively, the operating specifications of some facilities in the fuel cycle may be adjusted so that they require less material. The most appropriate solution will likely depend on the specific context for the modelled state.

These considerations are especially relevant for fuel cycles in which facilities are used for both civilian and military purposes, since in these cases the demand for resources is often higher, and key facilities may represent potential 'choke points'. These models should be carefully constructed so that both programmes can operate as smoothly as possible. This is especially important if the model is representing a sophisticated nuclear weapon state like the United States or Russia. This is also true for models involving a clandestine nuclear weapons programme, as any disturbances to known operating conditions are likely to attract attention.

For example, if the state launches a military programme to produce HEU for weapons at a similar time to launching a civilian LEU reactor, then the overall demand for uranium hexafluoride will be much higher than if the country was only producing plutonium weapons. Although it could be possible for the modelled state to import stocks of yellowcake to satisfy this demand, it may not be appropriate in all scenarios, especially if the modelled state is developing a clandestine weapons programme.

Alternatively, the timeline could introduce enrichment at an earlier stage in the state's development history. This would provide a longer period of time for the enrichment process to take place, and it would shorten the number of years needed to accumulate source material to convert into uranium hexafluoride. Alternatively, the state could import stocks of yellowcake for either fuel cycle to help alleviate the pressure, but this decision needs to match the modelled state's profile: larger and wealthier nuclear weapon states are more likely to be able to afford yellowcake stocks, but the same may not be true for smaller nascent nuclear weapon states and could be impracticable for a clandestine nuclear programme wishing to avoid international attention.

### 6.2.6 Modelling a nuclear weapons arsenal

The previous sections illustrated how a country's nuclear fuel cycle can be modelled to reproduce its nuclear facilities and to map its production of special fissionable material. This section explains which parameters concerning a country's nuclear arsenal are important to address in a disarmament model, and how these impact

**Box 6.14** Assumptions underlying the nuclear complex of Example Country 2

The following are the main assumptions that were drawn from the country profile and disarmament context document, prior to developing an overview of the nuclear arsenal of Example Country 2.

- At the point of disarmament, the nuclear arsenal of Example Country 2 is small, consisting of roughly 50 warheads. This nuclear arsenal was intended to be fully deployed and visible to Example Country 2's adversaries.
- The decision by Example Country 2 to pursue nuclear weapons is taken at the end of the 1970s. Its first test is conducted at the end of the 1980s, and is followed by a series of tests over the next two decades. The final nuclear test of Example Country 2 is conducted immediately before the disarmament agreement is negotiated and concluded. From its first nuclear test to the moment of disarmament, Example Country 2 has approximately 25 years for weapons development and production.

**Goals:**

- Example Country 2 wanted to produce an arsenal of reliable, miniaturised, missile-deliverable megaton-range thermonuclear weapons.

**Challenges:**

- The scientific personnel of Example Country 2 lacked highly advanced theoretical knowledge and manufacturing capabilities, which resulted in Example Country 2 encountering difficulties in producing miniaturised, highly efficient weapons.
- The scale of the nuclear arsenal of Example Country 2 was constrained by its limited access to fissile material and by the lack of missiles that were powerful enough to carry such unsophisticated warheads reliably and to a satisfactory range.

on verification efforts. Modelling a country's nuclear arsenal and its surrounding infrastructure requires both technical and political considerations. As such, this activity draws from both nuclear fuel cycle modelling and disarmament scenarios.

The first step in creating a comprehensive picture of a country's weaponisation activities and nuclear arsenal is to identify the main assumptions underpinning the country's nuclear programme. In the framework of the methodology outlined so far, these are captured in the country profile and in the disarmament context document. The relevant information on weaponisation from those two sources concerns the size of the country's nuclear arsenal and the country's history of nuclear weapons research and development. In addition, these documents should also illustrate the main goals the country pursued while developing nuclear weapons—for example, a large arsenal deployed across a series of launch sites, or a small arsenal on mobile platforms—and the main challenges its nuclear programme had to face. This type of information is drafted early on, as a guide to the creation of the disarmament scenario and nuclear fuel cycle model. This helps to focus the development process on specific circumstances, and on specific verification challenges. Box 6.14 provides a list of basic assumptions drawn up for Example Country 2 (see Sections 6.1.1 and 6.1.2 for more information on Example Country 2), prepared by VERTIC while investigating disarmament verification methodologies.

## Classified and proliferative information

The issue of modelling nuclear weapons-related activities while avoiding spreading proliferative information has already been touched on in previous sections (see Section 6.2.5), but bears repeating.

For some information, such as the composition and mass of a nuclear weapon's fissile pit, it is possible to find figures, such as an approximate weight in kilograms. These figures still lack crucial details, such as the precise isotopic composition. Other information is more difficult to come by, or to confirm, such as the weight and composition of a fissile spark plug in a two-stage thermonuclear device.

The purpose of modelling these fissile components is to provide a way to test material accountancy procedures during and after weapons dismantlement, which is known to be a crucial step of the disarmament verification process. However, this does not mean that the model requires minute, fully realistic detail to be able to capture this aspect. It is possible to effectively model this type of data by taking ballpark figures from what is generally known, and establishing a value for those details that are not publicly available. This type of data does not aim to reproduce reality in a way that could be dangerous to international security, but to provide a placeholder that can be used within the scenario's constraints, while respecting its internal consistency.

## Describing nuclear arsenals

Once all the main assumptions and the general scope of the modelled nuclear programme are known, modellers can move on to describe the different types of nuclear weapons and nuclear explosive devices that have been developed by the country. For example, the assumptions listed in Box 6.14 would lead to an arsenal including five different types of weapon. Of these, the first is just an adaptation of the original, crude test device, in a gravity bomb casing, and the second is another unsophisticated weapon, suitable for missile delivery. The third and fourth types of weapon introduce some more advanced technology that makes the weapons more effective and increases their yield. The fifth type of weapon produced by Example Country 2, after a considerable development and testing programme, is the first high-yield thermonuclear weapon. This fulfils the ambitions of Example Country 2, however, it must be noted that the country's arsenal is not only composed of these advanced weapons, but also of previous types that are less effective and reliable. For comparison, modelling a country with a far larger nuclear complex and a longer nuclear history, similar to the US, would result in many more classes of weapons and, most likely, a range of delivery systems. Furthermore, such a country probably produced other weapons of cruder design in the past, which would have been retired from deployment or even dismantled. On the other hand, a country with a very small and rudimentary nuclear arsenal may be limited to one single weapon class, or even to explosive devices not suitable for ready delivery.

In order to describe the different types of weapon, the following criteria should be addressed.

### Weapon type

This indicates the general design of the weapon. For example, basic fission weapons can use a 'gun-type' or an 'implosion' design, while thermonuclear weapons employing nuclear fusion usually use a two-stage design, also known as Teller-Ulam design. Other relevant design features, such as the use of fission boosting—in which a small fusion reaction is used to boost the output of a normal fission weapon—should also be indicated, as they affect the weapon's efficiency, and through that, the weapon's yield and fissile content. Design features that make a weapon more efficient can increase the weapon's power, while decreasing the weight and mass of the weapon.

### Fissile content

This relates to the type of fissile material used in the weapon's pit: whether it is plutonium, highly enriched uranium, or a mixture of the two. It should provide an indication of the amount of fissile material contained in the weapon (for notes on how to represent this type of data, see above).

## Yield

The yield of the weapon, in terms of energy output and destructive power, will be expressed in kilotons or megatons. Knowing the type of weapon and the yield can help to provide an estimate of the weapon's fissile content.

## Delivery system

The model should specify whether the device is a gravity bomb, a warhead for missile delivery (and the type or types of missile capable of delivering it), or another type of device. While this is not directly relevant for the purpose of modelling fissile material in weapons complexes, it is relevant to understand the role of the weapon in the country's arsenal and nuclear policy. Furthermore, delivery vehicles and casings can be used along with other non-fissile components to corroborate verification findings (see below).

## Other design characteristics

It can be useful to provide further detail on specific aspects of the weapon's design. For example, modellers could indicate whether the weapon uses a hollow or levitated pit, or an asymmetrical pit. This type of detail has an impact on the weapon's efficiency, safety and reliability. It is worth noting that only the most general principles of these technologies are understood in the open source.

## Non-fissile components

Non-fissile components cover a wide range of different materials and technologies. Some of these are crucial components of the weapons, such as the arming, fusing and firing mechanisms that trigger the explosion. Others are specialised and advanced technologies used to increase the efficiency of the weapon, such as neutron initiators, or fission boosting devices. While tracking flows of special fissionable material is important in verifying disarmament, non-fissile components can also play a part in the verification process. These items can be identified through visual inspection (when compatible with the need to protect sensitive information), and identification marks such as serial numbers can be compared with documentation on the production and deployment of weapons. Credibly identifying these components as belonging to a weapon can help substantiate conclusions obtained through different verification techniques, and boost confidence that the inspected item is a real nuclear weapon.

Once the different weapon classes have been described, it is possible to list the country's arsenal in detail. The general assumptions and scope concerning the country's arsenal should indicate the number of weapons at the moment of disarmament. These should be divided among the different types of weapons, as appropriate following the premises. Furthermore, attention should be given to weapons that are held in reserve and weapons that have been retired, in addition to deployed weapons.

## Nuclear weapon development and testing

It is important to describe the different weapon classes that compose the modelled country's arsenal in detail to provide the specific, actionable information that is necessary to model the disarmament process (see next section) and devise verification solutions. However, contextual information on the history of the country's development and production of weapons can also be important, especially when testing verification solutions through simulations. These details will come together in a timeline representing the entire history of the country's development, testing and production of nuclear weapons. When compiling the timeline, it is important to make sure the modelled state's nuclear weapons activities are consistent with the type of technology the country would possess at that point in time, and with the amount and type (or types) of fissile material the country is able to produce. These matters are discussed in greater detail below, starting with the issue of technological complexity.

The first step in completing the timeline of the country's nuclear weapons activities is to chart the date when the country first produced nuclear weapons, and the date when each of its different types of weapons was first produced. The main consideration to keep in mind here, is that these dates must be consistent with the technological complexity of each weapon class. It is possible to use the weapon type and design characteristics (as described above) as reference, and research when similar technologies were introduced in other nuclear-weapon states. For example, a two-stage (Teller-Ulam) thermonuclear device was first tested in 1952. Therefore, it would be difficult to justify the possession, by any modelled country, of such a weapon before that date. On the other hand, it could be appropriate for the modelled country to use technologies that are considered dated and obsolete, if this reflected the notion that the country faces significant access problems to either know-how or material. Furthermore, the intervals at which different weapons are introduced should also be plausible and consistent with the modelled state's ability to develop new technologies, and with what is known about its efforts to acquire nuclear weapons (as outlined in the country's profile and in the disarmament context document, see Section 6.1.1). For example, a country could not realistically develop advanced, miniaturised thermonuclear warheads without years of research and, most likely, testing. Exceptions may be possible, for instance, if the modelled country received support from more advanced states.

After the main dates have been established, it is possible to chart the country's research and development activities. Building on what is known of the country's internal politics, and of who had control of the nuclear fuel cycle, modellers and scenario developers can draw up a narrative describing which institutions were involved in the country's nuclear weapons programme and how the programme was organised. By looking at the different weapons coming into production, and at the technologies they employ, it is possible to outline specific research strands focusing on different concepts and applications. Depending on the type of country, and on the technology, some of these research strands may have a very precise focus on a specific technology, and some might have a wider scope. Furthermore, these strands may progress in relative isolation, or may engage in exchanges of technologies and transfers. A great deal of scholarship has gone into researching the history of the nuclear programmes pursued by different countries.[34] These sources can be used to inform this stage of the work, both for models that reproduce existing states, and for models based on hypothetical countries.

The next step in creating a credible and detailed story of a country's nuclear weapons complex and programme is to outline the country's history of nuclear tests. By looking at the different research strands, and at the weapons they developed, modellers can add nuclear tests to the timeline. Each single test can be briefly described according to these parameters:

- Date and location;
- Type of test: atmospheric, underground, underwater, out of atmosphere;
- Type and amount of fissile material consumed;
- Type of device tested, and goals for the test;
- Yield of the explosion;
- Test result: success, failure, other options.

When laying out the country's nuclear testing history, it is important to refer to the country's history and wider geopolitical context, as international norms on nuclear testing have changed over the years. For example, atmospheric nuclear testing was common throughout the 1940s and 1950s, but gradually fell out of favour, starting with the 1963 Partial Nuclear Test Ban Treaty (signed by three of the NPT Nuclear-Weapon States).

Issues such as the organisation of the country's nuclear weapons programme and the complete history of the country's nuclear tests may seem removed from the core problem of verifying future nuclear disarmament, and especially with the verification of nuclear material. However, this type of background can provide useful information to corroborate findings of other weaponisation activities, especially when running a simulation. For example, inspectors may want to know additional details of the country's past production of weapons, and cross-reference that with data on past fissile material production (see Section 6.2.4 and 6.2.5), to ascertain that all weapons have been accounted for.

## Modelling the production of nuclear weapons

The final stage in creating a timeline of the country's weapons activities is to chart its weapons production year by year. The number and type of weapons in the country's arsenal has already been established (see above). By knowing the amount of weapons-usable material that the country can produce each year, and having an estimate of the yearly throughput of the country's weapons assembly facilities, it is possible to determine how many weapons, and of which kind, were produced each year. This will provide a timeline of the country's accumulation of nuclear weapons. At its simplest, the build-up process may be fairly linear, with the country gradually producing weapons. On the other hand, it may be desirable to introduce some more complexity, for the sake of realism and credibility. For example, as mentioned above, a country might gradually phase out older weapons, retiring them to storage or even dismantling them, and introduce new and more advanced weapons instead. Alternatively, a country might initially undergo a large expansion, but then reduce numbers as a result of unilateral decisions or partial disarmament agreements, before the moment of disarmament described in the scenario. When considering the amount of fissile material employed and the number of devices assembled each year, it is also important to take the country's nuclear tests into account.

It is important to check that the decisions made about the country's arsenal and about the nuclear fuel cycle model (as outlined in the previous sections) are consistent. Discrepancies between these two elements may lead to unrealistic or impossible scenarios, in which countries produce too many or too few weapons compared to their capacity, without a credible justification for it. For example, a stated end result for a given model could be to have a country in possession of 100 weapons, but the country's ability to produce fissile material according to the model might not be sufficient to achieve those numbers in the allotted time. In that case, one of the two elements would have to be changed to ensure consistency. The choice of which element to alter is largely dependent on the overall aims of the scenario. In a scenario focused on verifying the dismantlement of a large arsenal, choosing to downsize the number of weapons may be counterproductive. Alternatively, a scenario that is focused on applying verification procedures to a small nuclear fuel cycle might be better served by keeping the nuclear facilities as they were initially modelled and reconsidering the expected size of the country's nuclear arsenal. Of course, a mismatch between the state's aims and its actual capabilities could be part of the scenario, and be justified by elements in the narrative. If that is the case, modellers should be careful in noting it and making the rationale for the mismatch explicit. For example, a country might aim to produce 200 weapons, but suffer technical limitations that constrain it to a smaller arsenal.

## Logistics and facilities

The final stage of outlining a country's weapons complex is to map the various facilities it comprises, starting from the production of fissile material and ending with the military facilities in which weapons are assembled, stored and deployed. Box 6.15 provides a list of some of the types of facility that can be part of a nuclear weapons complex.

**Box 6.15** Sample facilities in a nuclear weapons complex

- Nuclear reactors;
- Uranium enrichment plants;
- Spent fuel reprocessing plants;
- Uranium and/or plutonium metallurgy and pit fabrication plants;
- Facilities used for production and storage of weapons casings, arming, fusing and firing systems, and delivery vehicles;
- Research reactors for the production of tritium (fusion fuel);
- Electronics laboratories;
- High Explosives fabrication facilities;
- Material testing and hydrodynamics sites;
- Weapons and explosives assembly sites;
- Interim storage sites for pits and weapons, used during fabrication and assembly;
- Weapons storage sites;
- Weapons deployment sites

This list is in Box 6.15 is not exhaustive. Weapons complexes may differ from each other in the type and configuration of their facilities, and in the way they are centralised or distributed in a territory. Providing maps and information on facilities dedicated to weapons manufacturing raises the same issues of proliferation and national security that are raised by using highly accurate data on fissile material, as discussed above. However, weapons complexes around the world have been studied and reported on in great detail, through governmental reports, publications by third parties, as well as visual analyses of satellite pictures. Many of these resources are easy to obtain, and it is possible to use them as models, or to study their recurring features, in order to design a complex for a hypothetical country.[35] Mapping the key steps of weapons assembly (or disarmament) can be useful to test procedures aimed at verifying the dismantlement process. For example, research and simulations could focus on establishing and maintaining continuity of knowledge as the weapon is disassembled and the fissile pit is first removed, then sent into storage or destroyed. This could involve charting the movements of the items between different locations and interim storage, identifying ways to secure the locations and ensure that unauthorised entries and exits are detected, discussing the initial identification of the item (a major issue on its own) and the application of tags and seals. However, once the key nodes and activities have been charted, it is not necessary to provide in-depth information (even in the rare cases in which that could be possible), and the main proliferation-sensitive steps can be 'black-boxed', by specifying an input and an output without describing the actual process.

The aim of outlining a country's weapons complex and nuclear arsenal is not, ultimately, to reveal information about how nuclear weapons are produced. Rather, this data is required to test and validate verification solutions developed using this methodology. Because of this, it is reasonable to accept internal consistency and adherence to general principles that are known to be true, instead of demanding full accuracy.

### 6.2.7 Modelling the disarmament process

The previous sections showed how fuel cycle models can be constructed to provide detailed quantitative information for representations of different nuclear weapon programmes. The process for developing a fuel cycle model that consists of civilian operations (Section 6.2.4) and military facilities (Section 6.2.5) can be created to generate data on quantities of uranium that progress through the fuel cycle to form the pits (either HEU, plutonium or a mix of the two) for nuclear weapons (Section 6.2.6). In this section, discussion turns to modelling specific activities associated with disarming a nuclear weapons state.

#### Dismantling a nuclear arsenal

As noted in previous sections, nuclear weapons, and the programmes nuclear-armed states develop to construct and sustain them, are complex and diverse. As such, nuclear disarmament is also a complex undertaking involving a diverse array of activities and connected facilities. Given that nuclear weapons programmes can develop in various ways—employing different facilities, fissile material options and weapons designs—it is not surprising that the disarmament process will also vary.

The steps to disarmament depend on the nature of any hypothetical disarmament agreement that has been developed for the disarming country and other states and entities. The steps also depend on the individual characteristics and profile of the disarming state. Although much of the disarmament process will therefore be tailored toward the specific political and technical context under which an agreement was made, there are, nevertheless, some steps that are likely to be common to most disarmament situations.

Essentially, the likely steps of a proposed disarmament process can be postulated on the basis of what has been seen over the years in the form of largely unilateral nuclear arms reductions, such as those conducted in the US at its Pantex Plant. A non-exhaustive list of these steps is presented in Box 6.16.

In addition to these steps, the actual process of dismantling each weapon can progress through various activities arranged along a disarmament spectrum. The spectrum of disarmament activities is best understood from the perspective of reversibility[36]—the time and effort required to undo the disarmament process and to reassemble and rearm. For example, the removal of nuclear weapons from delivery vehicles can be seen as a step that can be reversed quickly. Essentially, this is the most simplistic step in the dismantlement process. Dismantlement

**Box 6.16** Stages of nuclear weapons disassembly

1. Numbers and types of weapons to be removed from deployment or from a stockpile are nominated and consigned, in batches, by specialised transport, to the original assembly facility where they were created;
2. On arrival at the original assembly facility, weapons are likely to be deposited into an interim store;
3. Weapons then move onto a disassembly line and undergo mechanical disassembly which includes:
    a. Removal from the shipping container;
    b. Removal of non-nuclear components (tail fins, parachute canister, pre-flight packages etc.);
    c. Removal of arming, fusing and firing components;
    d. Removal of any tritium containers; and
    e. Removal of the nuclear explosive physics package.
4. Final disassembly consists of removal of high explosives and other parts from the fissile material components (which may be uranium, plutonium, or both);
5. The disassembly results in a series of specially-packaged fissile material components, which will be consigned to high-security storage; again this is likely to be at, or near to, the assembly/disassembly facility.[37]

of nuclear weapons and the destruction of their components is a far more difficult and time-consuming step to reverse. If the disarmament process has involved the removal of facilities and the expertise required to reconstitute a nuclear arsenal, then reversing the disarmament process becomes even more difficult and time-consuming. It is possible to separate nuclear disarmament activities into an illustrative spectrum of nuclear disarmament activities in order of decreasing reversibility:

- Dismantlement of nuclear weapons;
- Termination of production of weapons-usable fissile material for nuclear weapons;
- Destruction or conversion of weapons-usable fissile material recovered from dismantled weapons or from stockpiles;
- Elimination or reversal of nuclear weaponisation activities related to the development and maintenance of nuclear arsenals;
- Placement of all civilian nuclear materials and activities under international safeguards, including the monitoring of converted fissile materials recovered from dismantled weapons.

Each activity in this list involves different technical procedures and technologies, and presents different challenges, especially from a verification perspective. To convert one weapons-usable fissile material production facility from military to civilian oversight, under IAEA safeguards, would entail relatively straightforward technical and procedural adjustments. Such a process may not take much more than a year to complete. In contrast, dismantling a large nuclear arsenal would involve a number of logistical challenges, the development of new tools and procedures, and take many years. This process may also generate a number of new safety and security risks.

## Modelling nuclear disarmament

When it comes to modelling the disarmament process, it important to consider the discrete disarmament activities identified in the disarmament agreement that will need to be built into the fuel cycle model.

The model should also account for realistic time intervals for each stage of the disarmament process. This involves recording the time it takes for deployed weapons to be returned to the assembly/disassembly facility and then to progress through the various stages of dismantlement to the subsequent storage or disposition of the weapon's fissile components. In many instances, these activities may only take a few months to complete. It may therefore be useful for the disassembly facility sheet, which contains data for the disassembly process (see Section 6.2.4 for more details on facility sheets), to be divided into monthly intervals, as opposed to the yearly intervals employed in the other fuel cycle facility sheets. This will provide the model with greater detail for each stage of the disarmament process as the warhead progresses toward final dismantlement.

At a basic level, the most useful and crucial information for the model relates to the movement of fissile material being removed from each weapon. The data contained in the assembly facility data sheet, which contains information on the construction of the nuclear weapons, will provide figures for the quantities of fissile material that constitute each pit for each weapon—these quantities are unlikely to change over time, even if the weapon is several decades old.[38]

As discussed in Section 6.2.4 and 6.2.5, the construction of nuclear fuel cycle models should aim to include information that is of most value for the model's eventual purpose. In this instance, the models that have been discussed here will provide quantitative information for future simulations aiming to verify the disarmament of nuclear weapons. It is therefore possible for those modelling the development of nuclear weapons programmes and their disarmament to include additional activities and components that are not discussed here. For example, models could be created to account for the destruction of deployment vehicles or track the movements of non-fissile components once separated from the warhead's physics package. However, this information is potentially excessive and could lead to an overly burdened model. It is therefore up to the modeller to decide what type of information best suits their purpose.

Once the disarmament process is underway, the model can track fissile material pits as they progress through dismantlement. This process is relatively straightforward. For example, if the disarmament agreement only requires that pits be placed in monitored storage or inaccessible locations indefinitely, then the model can just account for the number of pits (consisting of estimated quantities of special fissile material (see Section 6.2.5 and 6.2.6)) entering a storage facility. An accounting challenge, however, arises if the material is to undergo further disposition efforts. For instance, if a disarmament agreement requires pits to be chemically or mechanically malformed in order to render it useless for weapons purposes and to eliminate proliferation-sensitive pit shapes, then the facility sheet needs to account for the specific process employed as well as any loss of material. The same is essentially true for recording information on the adjustment of the pit's fissile isotopes away from a weapons-usable form. This process could involve diluting enriched uranium with non-fissile uranium such as $^{238}$U or 'burning' purified plutonium in a nuclear reactor. The facility sheets, in this instance, can contain the changing percentage of fissile isotopes for each batch of pits as they undergo treatment.

## Section 6 endnotes

1 The Integrated Field Exercises aim to develop and test the CTBTO's ability to conduct on-site inspections to search for evidence of whether or not a nuclear explosion has occurred. The latest full-scale exercise at the time of writing has been IFE14, which ran from 3 November to 9 December 2014 and was hosted by Jordan. For more information on IFE14, see: https://www.ctbto.org/specials/integrated-field-exercise-2014/.

2 Treaty accountable items are the items or objects that states parties to a treaty have committed to monitor and account for. For example, in a nuclear disarmament treaty, treaty accountable items may be nuclear warheads and the related delivery systems.

3 Baseline indicates the situation at the time the agreement enters into force: for example, the number and type of nuclear weapons and the stockpiles of weapons-usable nuclear material the country possesses.

4 *Uranium 2014: Resources, Production and Demand*. Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, p. 37.

5 *Uranium Mining Overview*, updated June 2015, World Nuclear Association; http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/Uranium-Mining-Overview/

6 *Conversion and Deconversion*, updated September 2015, World Nuclear Association; http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Conversion-and-Deconversion/

7 The IAEA defines LEU as 'enriched uranium containing less than 20% of the isotope $^{235}$U.' See 'IAEA Safeguards Glossary, 2001 Edition'. *International Nuclear Verification Series 3*. Vienna: IAEA, 2002, p. 31.

8 URENCO description of SWUs: http://www.urenco.com/about-us/business-activity/nuclear-fuel-supply-chain/separative-work-unit

9 US Nuclear Regulatory Commission description of gaseous diffusion: http://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html#2

10 David Bodansky. Nuc*lear Energy: Principles, Practices, and Prospects (2nd edition)*. New York: Springer, 2008, p. 201.

11 Uranium enrichment, updated November 2015, World Nuc*lear Association;* http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

12 *Getting to the Core of the Nuclear Fuel Cycle: from the mining of uranium to the disposal of nuclear waste*. Vienna: IAEA, p.5; https://www.iaea.org/OurWork/ST/NE/NEFW/_nefw-documents/NuclearFuelCycle.pdf

13 Richard Kokoski, *Technology and the Proliferation of Nuclear Weapons.* New York: Oxford University Press, 1995, p. 76.

14 Gareth Evans and Yoriko Kawaguchi, *Eliminating Nuclear Threats: A Practical Agenda for Global Policymakers*, Report of the International Commission On Nuclear Nonproliferation and Disarmament. Canberra: ICNND, 2009, p. 55.

15 David Bodansky. *Nuclear Energy: Principles, Practices, and Prospects (2nd edition*). New York: Springer, 2008, p. 181.

16 Richard Kokoski, Technology and the Proliferation of Nuclear Weap*ons. New Y*ork: Oxford University Press, 1995, p. 76.

17 *Nuclear Development in the United Kingdom*, updated January 2013, World Nuclear Association; http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/Appendices/Nuclear-Development-in-the-United-Kingdom/

18 Richard Kokoski, *Technology and the Proliferation of Nuclear Weapons.* New York: Oxford University Press, 1995, p. 78.

19 *Processing of unused nuclear fuel*, updated September 2015, World Nuclear Association; http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Processing-of-Used-Nuclear-Fuel/

20 *Mixed Oxide (MOX) Fuel*, updated December 2014, World Nuclear Association; http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/

21 This timeline, developed by VERTIC, shows the dates in which each facility came online. Arrows indicate the length of time that each facility operated for: black arrows represent civilian operations while red arrows represent military operations. The bottom portion of the timeline shows the major geopolitical events that characterised that period of time.

22 *Nuclear fuel cycle simulators*, Cyclus; http://fuelcycle.org/basics/fcs_background.html

23 *Introduction*, Cyclus; http://fuelcycle.org/basics/index.html

24 URENCO description of its business activity; http://www.urenco.com/about-us/business-activity/

25 The SCALE software package was first developed in 1976 and is used across the world by nuclear engineers and scientists, regulators, licensees and research institutes. SCALE has components that range from state-of-the-art object-oriented code in C++ and Java, to modern Fortran 95 codes following modular design, with legacy Fortran codes with algorithms originally designed in the 1960s. For more detail, see B.T. Rearden *'Verification Methods for the SCALE Code System',* Proc. Verification and Validation for Nuclear Systems Analysis Workshop II, 2010.

26 B.D. Murphy, *ORIGEN-ARP Cross-Section Libraries for Magnox, Advanced Gas-Cooled, and VVER Reactor Designs,* ORNL/TM-2003/263. Oak Ridge, Tennessee: Oak Ridge National Laboratories, 2004, p. 1.

27 Ibid.

28 Richard Kokoski, *Technology and the Proliferation of Nuclear Weapons.* New York: Oxford University Press, 1995, pp. 73-74.

29 David Albright, 'How Much Plutonium Did North Korea Produce?' in David Albright and Kevin O'Neill (Eds.) *Solving the North Korean Nuclear Puzzle.* Washington, DC: The Institute for Science and International Security, 2000, p. 114.

30 For a general overview of many aspects of the fuel cycle, see http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/. For a detailed discussion of nuclear reactors but also other aspects of the fuel cycle, see David Bodansky. *Nuclear Energy: Principles, Practices, and Prospects* (2nd edition). New York: Springer, 2008. For a good detailed discussion of enrichment technologies, see Allan S. Krass, Peter Boskma, Boelie Elzen, and Wim A. Smit, *Uranium enrichment and nuclear-weapon proliferation.* Stockholm: SIPRI, 1983; and US National Academy of Sciences, *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capability*. National Academies Press, 2004. For a good description of reprocessing, see *Spent Nuclear Fuel Reprocessing Flowsheet*, published by the Nuclear Energy Agency, Organisation for Economic Co-operation and Development. Paris: OECD, 2012.

31 Information for quantities of plutonium in the core were generated using ORIGEN-ARP. The reactor model was a Russian VVER-440.

32 See Richard Rhodes, *The Making of the Atomic Bomb.* New York: Simon & Schuster, 1986; Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb.* New York: Simon & Schuster, 1995; Chuck Hansen, *US Nuclear Weapons: The Secret History*. Arlington, Texas: Aerofax, 1988; and Chuck Hansen, *The Swords of Armageddon*, online at http://www.uscoldwar.com/.

33 The IAEA defines a significant quantity as 'the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.' Significant quantities for weapons-usable material are 8 kg of Pu, 8 kg of $^{233}$U, and 25 kg of $^{235}$U. See 'IAEA Safeguards Glossary, 2001 Edition'. *International Nuclear Verification Series 3*. Vienna: IAEA, 2002, p. 23.

34 See for example: Richard Rhodes, *The Making of the Atomic Bomb.* New York: Simon & Schuster, 1986; Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb.* New York: Simon & Schuster, 1995; Douglas Holdstock and Frank Barnaby, *The British Nuclear Weapons Programme*, 1952-2002. London: The Psychology Press, July 2003; and Lorna Arnold, *Britain and the H-Bomb.* London: Palgrave Macmillan, March 2001.

35 See for example: David Albright and Kevin O'Neill (Eds.), *Solving the North Korean Nuclear Puzzle.* Washington, DC: The Institute for Science and International Security, 2000; US National Nuclear Security Administration, *Fiscal Year 2014 Stockpile Stewardship and Management Plan.* Washington, DC: US Department of Energy, NNSA, 2013.

36 'Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement', in Procee*dings of the Institute of Nuclear Materials Management 38th Annual Meeting,* 1997.

37 David Cliff, Hassan Elbahtimy and Andreas Persbo, *Irreversibility in Nuclear Disarmament: Practical steps against nuclear rearmament*, VERTIC Report, London: VERTIC, September 2011.

38 For a discussion on the aging of plutonium pits, see Joseph C. Martz and Adam J. Schwartz, 'Plutonium: Aging Mechanisms and Weapon Pit Lifetime Assessment', *Journal of Minerals, Metals and Materials*, September 2003, at http://www.tms.org/pubs/journals/JOM/0309/Martz-0309.html

# 7. Conclusion

While the future of nuclear disarmament remains challenging to forecast, there are clear trends emerging among the initiatives that explore how it might be verified. These trends include an expansion of scope beyond nuclear warhead dismantlement to other forms of disarmament, and states that previously explored disarmament verification in unilateral or bilateral projects are opening their doors to a more inclusive approach. There is growing demand among states for new methods to explore nuclear disarmament verification that are broad, adaptable and accessible. This report has discussed a means of meeting this demand. It has focused on the development of an approach to examining nuclear disarmament verification in a variety of possible contexts. This approach uses hypothetical disarmament scenarios and fuel cycle models and aims to generate a set of practical, tested and accepted verification options and solutions.

Preparing to verify nuclear disarmament involves addressing a number of technical, legal and political issues. These issues reflect the complexity, hazards and sensitivity of nuclear technology. However, these challenges can be overcome through ambitious long-term planning, proactive and collaborative problem solving, and by building on the lessons and achievements in the field of verification to date.

The way in which disarmament is carried out will vary between states, depending on the characteristics of a country's nuclear weapon programme, and its wider military and civilian nuclear industry. However, it will likely include one or more of the following steps:

- Dismantling nuclear weapons
- Terminating production of weapons-usable fissile material for nuclear weapons
- Destroying or converting weapons-usable fissile material recovered from dismantled weapons or from stockpiles
- Eliminating or reversing nuclear 'weaponisation' activities related to the development and maintenance of nuclear arsenals
- Placing all remaining civilian nuclear materials and activities under international safeguards, including the monitoring of converted fissile materials recovered from dismantled weapons

The study of nuclear disarmament verification needs to be sufficiently modular and adaptable so that it can consider any disarmament situation that may emerge, and do so in a comparable way.

Several concepts on how nuclear disarmament can be verified have been brought forward over the years, but more work remains to fully explore, test and validate them. Simulation exercises can be particularly useful in this regard, and these should become the norm, not the exception. Simulations have already made an important contribution to the exploration of disarmament verification. The US-UK report on their technical cooperation for arms control verification points out that 'the opportunity to test and evaluate technologies and processes in operational environments is essential for understanding actual capabilities and feasibility.' Their research—underpinned by a series of joint inspection exercises—has concluded that 'the monitoring of nuclear warheads, components and sensitive processes is feasible' from a technical perspective. However, it has also concluded that many legal, technical, and classification challenges remain before a warhead dismantlement verification regime can be implemented.[1]

The US-UK collaboration is carried out under the 1958 Mutual Defence Agreement. While this enables both countries to share sensitive and classified information with each other, increasing the depth of their studies, it limits participation to just these two states. However, the UK-Norway Initiative has demonstrated that nuclear-armed states and non-nuclear-armed states can work constructively together to explore nuclear warhead disarmament verification and to appreciate better each other's perspectives and concerns. The latest exercise conducted by the initiative, in 2010, drew several important conclusions and like the US-UK initiative, it highlighted that managing access to a nuclear dismantlement facility is within the realm of the possible.[2] The UK-Norway Initiative has identified the need to build on its findings to date in a wider disarmament context and to incorporate new partnerships with other states. The recently launched International Partnership for Nuclear Disarmament Verification has also recognised the demand for a more inclusive discussion on disarmament verification.

If a comprehensive investigation and needs-assessment of nuclear disarmament verification is to be undertaken it will have to include more issues than the dismantlement of nuclear weapons. For example, research and trials are also required for nuclear materials disposition since, once a warhead has been verifiably dismantled, the uranium and plutonium would need to be accounted for too. It can be argued, as it has been in the past, that it is not relevant whether weapons are destroyed, provided that agreed amounts of fissionable material is transferred to peaceful uses.[3] The Trilateral Initiative, which involved the IAEA, US and Russia, developed tools and procedures that could be applicable here, but since they have not yet been fully tested, it is unclear how effective they are.[4]

The IAEA's role in verifying nuclear disarmament also remains relatively unexplored. The safeguards system is currently the only international instrument available for providing assurance that a state has all its declared material and activities in peaceful applications, and nothing remains undeclared. Furthermore, the IAEA has had experience verifying nuclear disarmament activities in South Africa, and to a lesser extent Iraq and Libya. Verification simulations will be valuable when assessing the capabilities of the IAEA safeguards system for monitoring a nuclear fuel cycle which once had a military purpose.

So, while more work is required to investigate particular disarmament steps, more work is also required to bring together the threads of existing verification capabilities, as well as studies and exercises carried out to date, into a more comprehensive approach. By building on the results of these exercises and filling the gaps in understudied areas, it should be possible to develop a range of verification solutions that can be applied in many possible disarmament situations.

To do this, it will be necessary to identify and address the key legal, political and technical aspects that are common to all disarmament activities and situations as well as those issues that are particular to a given circumstance. And, to enable a multilateral arrangement to be developed, it will be necessary to bring together more stakeholders and build expertise among them so that they understand what is involved in disarmament verification.

VERTIC's multilateral verification project runs several types of activity to support these aims including expert meetings, educational seminars, surveys and the development of technical resources. But, as this report has identified, simulations can serve two particularly useful purposes in this context: they can be designed to enable experts to identify multilateral verification solutions and options; and they can be designed to provide opportunities to stakeholders who are less familiar with the subject to learn about and appreciate it, thereby increasing their capacity to engage with this issue.

For a holistic approach—both in terms of scope and inclusiveness—to be realised, several activities will need to be maintained by the international community. These include designing strategies for equipment development; building on the experiences of drafting mutually-acceptable language for arms control and disarmament agreements; and constructing realistic disarmament scenarios and fuel cycle models to examine what needs to be verified, who might carry it out, and—through simulations—to establish how this might be done. The following section provides a summary of considerations to be taken into account when considering developing these activities.

## Equipment for monitoring nuclear disarmament verification

Monitoring equipment plays a central role in verification. Parties to a disarmament agreement must be able to observe specific aspects of each other's behaviour to build confidence that their agreement is being implemented properly and that cases of non-compliance will be detected quickly. The availability of accurate equipment which all parties trust to deliver accurate and authentic information, without obstructing or endangering non-proscribed activities, is therefore crucial. Trusted detection equipment can help to strengthen verification and can even encourage states to enter into agreements in the first place. Inaccurate and impractical equipment will have the opposite effect.

Equipment used to confirm the nature of a Treaty Accountable Item is typically bespoke. This equipment will have to overcome proliferation and security constraints, as well as safety and other operational considerations. These issues may impact the type and amount of access inspectors can have to a TAI.

The equipment that could be used to verify the processes (in contrast to items) involved in nuclear disarmament is less tailored, and could be applied to a range of disarmament activities. As with item-based verification, the information gained when examining these processes can reveal proliferative or sensitive information, and using equipment to monitor those processes can obstruct or interrupt them.

Tools such as tags and seals can help to maintain continuity of knowledge on declared treaty items in nuclear disarmament verification. However, applying tags and seals to sensitive and dangerous items, such as high explosive lenses, can be dangerous, and may contravene the security measures required by the verified party. Items may also have to be moved or adjusted frequently during nuclear disarmament, making the application of tags and seals potentially impractical.

Equipment also exists that might be used to confirm the absence of *undeclared* items or activities. For example, current all-source approaches to verifying the completeness of non-nuclear-weapon-state safeguards under the NPT could be applied to nuclear disarmament. However, the risks of false indications of undeclared items or activities, and the subsequent intrusion of any follow-up inspections, will make its application to nuclear disarmament even more contentious than its application to nuclear non-proliferation.

Research and development efforts to date have produced a range of technologies that could be applied to verify nuclear disarmament. However, only limited work has been carried out to explore how this equipment could be deployed in the context of a nuclear disarmament agreement. The pursuit of nuclear disarmament verification solutions should therefore incorporate an equipment development strategy that can explore specific verification tasks, identify equipment constraints, generate technical specifications, and create accurate and trusted disarmament monitoring equipment. This strategy should take advantage of existing tools and procedures adopted by the IAEA and its member states for the development of safeguards equipment, as well as those developed through disarmament verification projects in Norway, Russia, the UK, and the US. A thorough needs assessment and gap analysis could show that some existing equipment can be adapted for new verification purposes, while other verification tasks may require the development of novel technologies.

## Drawing inspiration from the history of verification agreements

Efforts to date across the field of arms control and non-proliferation verification have also provided information that can be used to assess how proposed arrangements for multilateral verification systems might be codified into written agreements.

Verification aims to generate assessments of parties' compliance or non-compliance with an agreement. The ability to achieve this rests not only on a shared understanding of what constitutes compliance or non-compliance, but also on a shared understanding of the tools and procedures available to discriminate between the two. It will be important to codify these shared understandings clearly and systematically into a written agreement in such a way that prevents subsequent misinterpretation. The exploration of hypothetical verification agreements can provide one route to a shared understanding of the scope, features and robustness of a potential verification regime, and can help build confidence among states on the terms and formulations (in other words, the language) to be used in such agreements in the future.

Existing verification agreements demonstrate a generic structure that reveals the principles, practices and procedures that constitute a verification regime. These agreements also provide a repository of language and terminology that can contribute to exploring hypothetical verification agreements. Although existing verification agreements are unique products of the political and technical circumstances of their development, they provide useful examples and lessons, both from the commonalities that can be found across them, and in how particular technical issues were addressed and any challenges overcome.

## Simulating verification

In order to have practical multilateral verification solutions ready for a range of possible disarmament futures, it will be necessary to examine and test potential verification arrangements in realistic and relevant contexts. Such simulations should take into account the various research initiatives noted above, the tools and equipment they have developed, and the common understandings reached to date about verification procedures and definitions.

The political, technical and legal context of nuclear disarmament—reflected in the domestic politics and international relations surrounding nuclear weapons, the size and composition of nuclear weapon programmes, and the domestic and international legal structures that govern states' behaviour—can be incorporated into disarmament verification simulations that explore the verification of existing or hypothetical disarmament agreements. The legal and political context of nuclear disarmament can be laid out in 'scenarios' (as defined by this report in Section 6), and the in-depth technical context of nuclear disarmament can be established by nuclear fuel cycle 'models' (discussed in Section 6.2).

To function properly, verification simulations should have a well-defined objective regarding the questions it should explore, and the problems it should solve. Planning a simulation also requires identifying the types of participants that should be involved; the tasks that they should carry out; the materials they can draw from; the medium in which the simulation is conducted; and the approach taken to direct and record activities within the simulation.

These simulations can explore technical issues associated with the role of monitoring equipment in verification from several angles. Such simulations can explore the application of a single known monitoring technique to a range of disarmament activities, or alternatively, analyse the equipment requirements presented by a single disarmament activity. They will need to be supported with detailed technical modelling to properly represent disarmament activities, and to provide enough information to evaluate the monitoring equipment that might be involved in verifying these activities.

Verification simulations can also be used to explore the legal issues that need to be addressed to reach an agreed understanding of a verification system, including its procedures and definitions, and its compatibility with other legal requirements. They can draw on existing or hypothetical agreements to provide a foundation on which to develop and explore common understandings of nuclear disarmament verification.

The exploration of policy issues related to current or future nuclear disarmament initiatives can also be achieved through use of these simulations. For example, such simulations could draw on existing drafts of a Fissile Material Cut-Off Treaty (FMCT) to explore, and potentially demonstrate, their verifiability.

One way to design a framework and guidance for any such simulation is to establish a fixed context, or boundary conditions, in the form of a scenario. By using a template, such as that described in section 6.1, many different scenarios can be developed in a coherent, consistent and structured way. The scenario framework provides a way of designing verification simulations so that they address any and all key points under investigation, be they political, legal or technical. This structured but flexible approach allows for simulations to be adjusted relatively easily and consistently to suit different hypothetical situations or to take into account new information. For example, as suggested above, scenarios can be applied to current disarmament initiatives such as the FMCT or PMDA, or more hypothetical disarmament initiatives such as a nuclear weapons convention, to provide a useful outline of the political and legal factors these initiatives might encounter.

The scenario approach described in this report will provide an overview of technical issues in a given hypothetical disarmament situation. But this overview will need to be complemented by a detailed nuclear fuel cycle model if the practical steps of disarmament are to be examined in depth. These models provide an overview of the materials, processes, and technologies involved in creating and disarming nuclear arsenals. Models of hypothetical nuclear weapon programmes can be constructed from the ground up; from a foundational set of assumptions, through descriptions of the programme's development, to the use of software modelling tools to provide a detailed picture of the materials and processes used.

By providing an outline of the materials and processes involved in a hypothetical nuclear disarmament situation, these models can provide the basis for a verification 'needs-assessment'. They can be used to convey the technical aspects of a nuclear disarmament scenario to simulation participants, to explore the application of monitoring technologies to the materials and processes involved in that disarmament scenario, and to test verification solutions against descriptions of nuclear material flows.

There is no 'one-size-fits-all' model that describes the practical steps of nuclear disarmament: the types of technologies and the pathways for acquiring and disarming nuclear weapons vary between states. In addition, the detail and accuracy of these models is constrained by a modeller's access to information on the technical processes involved in nuclear armament and disarmament. Information about these processes can be proliferative, and is often highly classified. Any limitations on the detail and accuracy of a model should be taken into account when running a simulation and when considering its results.

## The future of multilateral verification of nuclear disarmament: the broad view

To date, the mechanics of nuclear disarmament and its verification remain understudied. The lack of attention given to this subject is particularly noticeable when compared with investment into studies in other areas such as nuclear security and nuclear non-proliferation. Little work has been undertaken to investigate the rationale for multilateral verification and how such an approach would work across the range of nuclear disarmament activities.

Detailed examination of the role of the IAEA in disarmament verification, or of alternative multilateral institutional arrangements, is correspondingly scarce. Yet, many states believe that multilateral verification will have a role to play in future arms reductions, especially on the critically important material disposition side. Both the IAEA secretariat and its member states note that the IAEA must remain ready to assist, as requested, with verification tasks under nuclear arms control or disarmament.[5] The organisation's member states, as well as civil society, can also stand ready to assist the agency in delivering on this objective and helping to investigate multilateral verification. Such efforts could include creating networks of institutions among member states to investigate multilateral approaches to disarmament verification, and collective activities to develop documentation outlining verification procedures, roles and responsibilities, and studies of political, financial and resource implications. A recent survey conducted by VERTIC suggests that member states are keen to engage in capacity building activities concerning the role of the IAEA in disarmament verification.[6]

Nuclear disarmament verification solutions will need to be reliable, precise, cost-effective, adaptable, inclusive and internationally accepted. It will take time to develop such solutions and work should be taking place now. In addition, the development and execution of verification simulations is not trivial. Their success depends on having a clearly defined objective, and the creation of scenarios and models that are sufficiently detailed and accurate to enable participants to reach this objective. This report has outlined a number of thematic areas where simulations could be particularly useful—including building verification capacity among more states, exploring existing disarmament initiatives such as the FMCT, and creating framework verification agreements for nuclear disarmament. Stakeholders, including states and civil society, should be able to define many valuable simulation objectives within each of these areas.

When the opportunity arrives for disarmament, it is important that verification solutions are ready and that states and the community of experts who are responsible for developing them should not be found wanting. If such verification solutions have not been developed, a window of opportunity could close long before such complex measures are developed. Indeed, if any actor opposes disarmament at that time, the unavailability of verification procedures would be a key argument.

It is also worth considering that the availability of reliable and tested multilateral verification solutions can support the view that transparent disarmament is viable and desirable. The existence of an internationally accepted verification system can therefore facilitate forward movement in states' disarmament positions, particularly if their chief concern is gaining assurance that other nuclear armed states are acting likewise.

## Conclusion endnotes

1 *Joint U.S.-U.K. Report on Technical Cooperation for Arms Control*, Washington: Department of Energy, 2015. http://www.nnsa.energy.gov/sites/default/files/Joint_USUK_Report_FINAL.PDF

2 *The United Kingdom-Norway Initiative: further research into the verification of nuclear warhead dismantlement*, Working Paper 31, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2015/WP.31, New York: 22 April 2015. www.un.org/en/conf/npt/2015/pdf/NPT-CONF2015-WP.31_E.pdf.

3 Allan Labowitz, *Project Cloud Gap and CG-34, Demonstrated Destruction of Nuclear Weapons*. US Atomic Energy Commission, November 1967. http://fas.org/nuke/guide/usa/cloudgap/aec-memo112167.pdf.

4 The 2000 Plutonium Management and Disposition Agreement between the US and Russia will draw on the results of the Trilateral Initiative to verify its provisions. However, precise verification arrangements with the IAEA have yet to be agreed.

5 *Member State Views on an IAEA Role in Verifying Nuclear Disarmament*, Verification Matters, No. 10, London: VERTIC, September 2015.

6 For a concise account of the IAEA's role in nuclear disarmament to date, see *The IAEA and Nuclear Disarmament Verification: A Primer*, Verification Matters, No. 11, London: VERTIC, September 2015.

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