CHAPTER 5

Investigating multilateral verification of nuclear disarmament: fuel cycle modelling for simulations

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Introduction

This chapter describes research directed by VERTIC and funded by the Government of Norway. The project, known as 'Supporting Multilateral Verification of Nuclear Disarmament' (MVND) engages the expertise of more than 50 researchers drawn from about a dozen organisations in seven countries.

The project aims to support the development of technologies and procedures that will enable a multilateral approach to verifying nuclear disarmament. It investigates how an intergovernmental organisation (IGO), such as the International Atomic Energy Agency (IAEA), can verify a wide range of nuclear disarmament scenarios. Accordingly, the project places an emphasis on verification of the whole nuclear fuel cycle, rather than focusing on warhead dismantlement alone.

A key feature of the MVND project has involved creating multiple nuclear fuel cycle models of hypothetical nuclear weapon states, to provide baseline data for disarmament simulation 'test-beds'. This data provides a research platform, which government, non-government and international actors can use to explore verification challenges in a range of hypothetical scenarios. This chapter will discuss the construction of these models, and how they can be used for the investigation of verification challenges.

While it is possible to conduct a desk review of the various technologies, procedures and methodologies applicable to future verification challenges, there is presently little ability to thoroughly explore any specific and practical situations in depth. There are, however, several valuable efforts in this field that are worth noting. For example, live-play scenarios have been carried out with personnel on the ground in real and mocked-up nuclear facilities, dating back as far as 'Project Cloud Gap' in the 1960s, which aimed 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.

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.

By the middle of the 1990s, optimism for nuclear arms control had grown significantly in the US. The US Department of Energy's Office of Arms Control and Nonproliferation commissioned technical studies into the monitoring of nuclear warhead dismantlement with the expectation that such actions would be included in a third Strategic Arms Reduction Treaty (START) between the US and Russia. This was optimistically expected to include provisions for warheads on both sides to become treaty accountable items.

At a similar time, the Trilateral Initiative brought the US, Russia, and the IAEA together for collaboration, exploring techniques for verifying the transfer of military plutonium (the fissile material used in key components of nuclear weapons) to civilian uses. Over the course of 98 meetings, the initiative surveyed 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.

Also, in 2000, the US and the UK started an on-going cooperation to explore technologies and methodologies. These included ways to allow foreign inspectors to enter a nuclear site and make monitoring measurements, without revealing sensitive information ('managed access'). Additionally, the co-operation studied 'information barrier' approaches to protecting classified data, while allowing inspectors to maintain continuity of knowledge over monitored items, and to gather information about the authenticity of these declared items. These efforts were aimed at developing widely applicable solutions that would enable the monitoring and verification of potential future nuclear disarmament initiatives.

More recently, further collaborative work between countries has been taking place. The UK and Norway—with contributions from VERTIC—established an initiative to assess approaches to non-nuclear-weapons-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.

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. The IPNDV held its second plenary meeting in Oslo in November 2015, where it finalised the Terms of Reference for each of the three working groups that are established under the Partnership, and decided to focus its attention on warhead dismantlement as a first priority, while acknowledging that at a later stage consideration of wider aspects of the nuclear weapons cycle would need coverage too.

Also in 2015, the UK–Norway Initiative announced that it will seek to work with additional countries. In addition, recently, a group of research institutes in Germany have come together to form a 'nuclear disarmament verification network' to discuss and explore technical approaches to verifying nuclear disarmament. A 2015 publication by the network recommends that their collaboration should be expanded to the European level, drawing on a wealth of nuclear verification experience on the continent.

Despite these efforts, testing verification solutions on real facilities and materials is often expensive, legally complicated and politically sensitive, and opportunities to do so remain largely out of reach. The UK–Norway Initiative, for instance, has provided valuable insights into verified warhead dismantlement, but not with real warheads, and not in real operational areas of nuclear weapons dismantlement facilities. Progress has been gradual and restricted to one aspect of nuclear disarmament.

Building on all this previous work, VERTIC's MVND project has begun to develop 'verification simulations'. The purpose of these simulations is to enable groups of stakeholders to discuss, negotiate, and test individual or integrated procedures and equipment for verifying hypothetical disarmament environments. These simulations are created by combining detailed nuclear fuel cycle models with a variety of potential disarmament scenarios, creating a test-bed environment to generate a broad range of consistent, coherent and realistic verification challenges.

This chapter will discuss the methodology for constructing the model component of these simulations. In order to appreciate the value of a model, it is first necessary to understand its intended end purpose. Accordingly, the next section will briefly describe how models can be paired with a variety of hypothetical scenarios to form the simulation environments, before moving on to describe the step-for-step process of constructing a model and providing examples that have been developed by VERTIC.

Modelling research based on the creation of realistic modelled states

Simulations

It is not unusual for arms control, disarmament and non-proliferation regimes to use simulations to explore or test practices and procedures. Through simulations, participants can practice activities in a non-classified, apolitical, repeatable and focussed manner, which help to build confidence that verification is achievable. Replicating real disarmament activities—and the technical, legal and political dynamics surrounding them—in a more hypothetical setting can identify the strengths and weaknesses of potential disarmament verification approaches while avoiding the possible consequences of getting a real-life activity wrong. The use of simulations is, of course, a tried and tested technique used in a large range of public and private sector activities, as well as in the military.

Simulations designed to investigate verification challenges must be implemented in a way that maximises the value of their contribution to disarmament verification efforts. It is important to agree on a clear objective for the simulation—what it aims to achieve in the real world. This overall objective should guide the design and generation of the hypothetical disarmament scenarios and the modelling of nuclear weapons programmes so that they can be of most use for exploring the simulation tasks.

The design of the simulations must provide a detailed and credible environment from which simulation 'players' can complete their tasks without recourse to preconceptions or prejudices. This environment needs to be described in a coherent and unambiguous way so that it can be understood and held in the minds of each simulation player—the substance of this environment is thus generated through information such as maps, diagrams and data reference materials. It is these elements that are produced as part of the scenarios and models.

At present, the simulations being developed by the MVND project consist of the following components:

- *Disarmament scenarios*: these portray a specific, discrete instance of disarmament, which can be based on existing or hypothetical countries and international 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—for example, through a fictitious disarmament agreement.
- *Nuclear fuel cycle models of nuclear programmes*: these represent a country's nuclear fuel cycle, from the acquisition of nuclear source material through to weapons production, providing detailed information on individual nuclear facilities and on mass flows of nuclear materials. Nuclear fuel cycle models are prepared through research, calculations and dedicated software, with the aim of providing as realistic a picture as possible.

Each model is designed to supply quantitative data on nuclear material production, use and storage for any given period of time (usually year-on-year). The nuclear fuel cycle models are detailed representations of military and civilian nuclear fuel cycles that describe—in as much detail as is practical—the fictitious state's nuclear history. They describe when facilities were built and entered into operation, as well as the operating conditions of those facilities and the types and quantities of materials involved. These 'building blocks', which allow the reconstruction of entire nuclear complexes, have been researched and selected by VERTIC researchers, in consultation with other experts from the nuclear industries, including military production environments.

Ultimately, the facility layouts and the fissile material data produced by the model, together with an appropriate disarmament scenario, provide the foundation on which simulation players can begin negotiations for a formal disarmament verification agreement and, subsequently, for a variety of other more detailed 'verification solutions'. Achieving this requires simulating the movement or transformation of nuclear materials—from nuclear weapons dismantlement through to storage and accountancy of these materials. Additionally, larger issues such as securing and decommissioning the many upstream fissile material processes involved in nuclear weapons production will also be modelled.

For all these process streams, key process points (where monitoring would most effectively be placed) need to be identified and verification procedures devised, agreed multilaterally—and formalised as an agreement or protocol. Potential 'verification solutions' (for example, likely types of monitoring technology) for these key locations, plus the bigger picture of achieving confidence in a complete verification scheme, can be explored through table-top, live, or virtual exercises.

These solutions can be validated against the modelled data and also against further sensitivity studies.

VERTIC is in the process of devising role-play simulation exercises by combining the models and scenarios that have been created in the MVND project. It is intended that invited subject matter experts will conduct these simulations in the form of a series of tabletop exercises. The combination of the example country model and the accompanying scenario provides a credible history for a country that will be used as a basis for these role-play exercises.

Participants in these simulations will identify key aspects of each scenario (from baseline declarations through to long-term monitoring) and will be asked to test the application of various verification approaches that have been identified through desk review of existing technologies, procedures and methodologies. The virtual world within which these tabletop exercises will operate will also, given their detail, allow participants to identify unexpected verification challenges, investigate and devise new approaches to overcoming these challenges, and, ultimately, generate lessons-learned, that help prepare future inspection teams for hitherto under-explored scenarios.

Alternatively, instead of involving subject-area specialists to explore and identify verification solutions, the simulations can be oriented for use as a capacity building exercise for stakeholders who are unfamiliar with disarmament verification and want to learn more about it and engage in the area.

Scenarios and a scenario template

For the models we have described to be of use, they must of course be based on realistic assumptions and data. Therefore, the MVND project established a credible 'scenario' to provide a legal and political background for each model, and for each subsequent tabletop simulation. Ultimately, the scenarios form a context for simulation participants to help them understand the simulation environment.

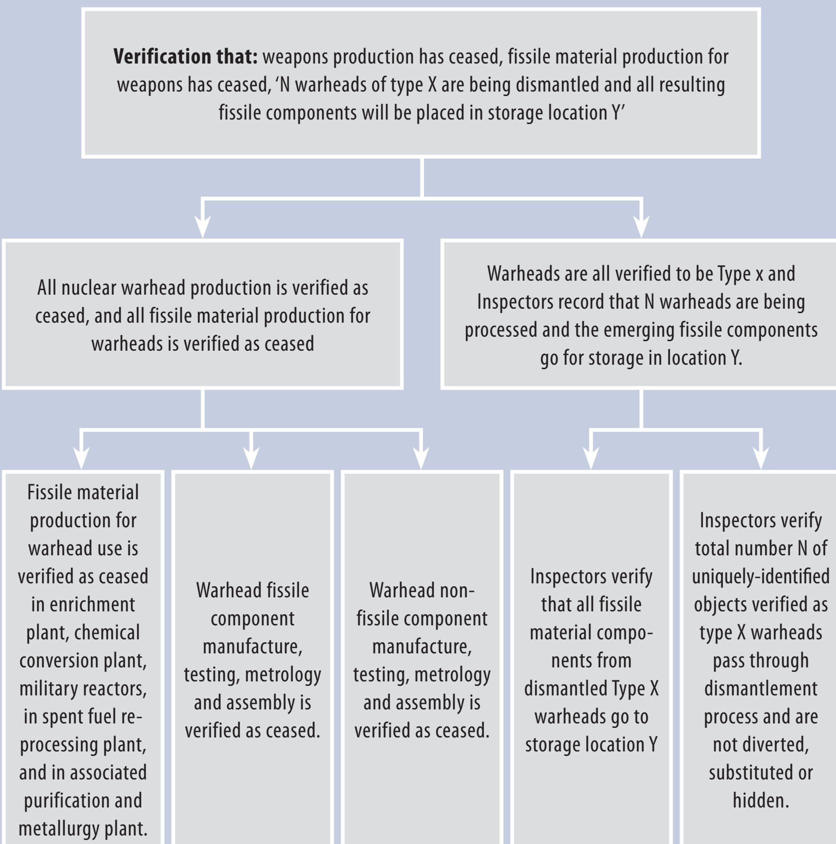
To optimise the simulation's effectiveness, it is important to provide all of the necessary information, without burdening the participants with superfluous details. With this in mind, and especially considering that the long-term objective of the MVND project is to have a series of different scenarios, covering a range of political and legal conditions, VERTIC and its project partners decided to create a *scenario template*, to be used when developing each scenario. This template is based around a series of questions about key variables, and various scenarios are created depending on the answers.

Key questions are:

- Is there an agreement or treaty governing the activities in the scenario? If so, who is party to this agreement, when was it signed, when did it enter into force, and what are its main obligations and subsequent verification tasks (such as the deactivation of nuclear activities, the disposition of material, or dismantlement of nuclear weapons)?
- Which country or countries will be the focus of the simulation (the modelled state and its treaty-partners)?
- Who is involved in the verification process?
- What is the state of relations between the various parties involved? Are any of the parties former adversaries, or allies? What, therefore, is the level of confidence required from the verification process?
- What is the agreed time scale for the activities taking place?
- What declarations are to be provided by the inspected state?
- What legal limits are there to the verification inspections (such as the obligation to ensure that no proliferation-sensitive data are released during the verification procedure)?
- Has the inspected state raised any political objections or set any specific limits on the extent to which verification activities can be conducted?
- Are there any nuclear safeguards agreements with the IAEA in place in the disarming country, prior to the verification process?

The answers to these questions provide the 'scenario': a detailed description of the undertakings to be verified, the context in which these are agreed, and the basic outline of how such an agreement will be verified. In doing so, they contain the seeds of both the technical and the political challenges that have to be overcome to successfully verify the hypothesised agreement. The disarmament scenarios produced also provide simulation participants with specific fictional roles, such as international inspectors, representatives of the inspected state or facility operators, and imply a number of specific activities or issues for which effective verification solutions must be applied.

Figure 1 A Logic-based breakdown of example declaration verification requirements at the beginning of a nuclear disarmament scenario where all military production is ceased and all warheads are to be dismantled



Main verification requirements—what kind of processes and items are important?

Charting the generic components of a verification scheme can provide a useful guide for devising of tabletop simulations.

Figure 1 above is a logic-based picture of a comprehensive verification scheme. It shows, in a hierarchical way, what a verification scheme should be confirming for a generic situation based on multiple types of treaty-accountable item at multiple locations in a nuclear complex.

Each descending level of the diagram unpacks the overall aims into successively more detailed components. This diagram represents only the top few levels level of what could be extended several more layers down, using Boolean logic to ensure that a complete picture is produced. Further elaboration of this technique is beyond the scope of this chapter. But, in summary, development of such a diagram moves toward identifying, at the lowest tier, the individual aspects and individual locations for which on-the-ground verification systems may be required. Equally, this sort of breakdown gives an indication of what level of detail is required in the modelling of the nuclear complex and its processes.

The research examples—modelling a fictitious nuclear fuel and weapons complex and the method used

The process for creating a fictitious nuclear complex history can be understood as a series of four stages that progress from broadly defined concepts to detailed specifics, and then onto the generation of applicable data. Essentially, the construction of each model progresses through four stages:

1. A principal decision on the type of country to be modelled;
2. Conducting desk-based open-source research to establish a credible timeline for the imagined state's history, available technology and operating conditions;
3. Producing a draft storyboard for the imagined state's nuclear industry development; and
4. Generating and gathering data for each facility for each year of the state's nuclear timeline.

Stage 1—concept stage

In this stage, research focuses on devising a suitable profile for the notional country to serve as a base on which a nuclear fuel cycle model and the main features of the state's nuclear weapons programme can be developed. To devise the profile, key decisions are made about the type of state that will be modelled. To allow the simulation of a broad range of potential verification challenges, the models developed under the MVND project represent an array of possible nuclear programmes of varying size and configurations. This enables researchers to identify whether different challenges emerge when different scenarios are applied to countries with nuclear programmes of varying sophistication and complexity.

At one end of the spectrum, models could represent a state with a highly-developed nuclear weapons programme complete with both military and civilian fuel cycles, overlapping nuclear material flows between the military and civilian cycles and a large stockpile of nuclear material, weapons and propulsion reactors.

At the other end, a model could represent a nation with a new and burgeoning nuclear capability, manifested by a single fuel cycle used for both military and civilian purposes, few nuclear weapons and an aspiration to develop an enrichment plant. Such a model, called 'Example Country 2', has been fully developed.

Another model, named 'Example Country 1', has been designed to strike a middle ground by modelling a country with distinct medium-sized civilian and military programmes, a nuclear arsenal of a few hundred weapons and a small nuclear naval programme.

Guided by the state's profile, the next step involves carrying out case study research into similar historical nuclear weapons programmes that relate to that type of state. For example, if the aim is to create a small nascent nuclear weapons state that undertook a heavily clandestine approach to weapons proliferation, like Example Country 2, then historical information can be drawn from the nuclear weapons programmes conducted by Iraq, Sweden, Libya, South Africa, Argentina and North Korea. This helps to establish a set of data for real-life examples, to inform the construction of the fictional models. Background questions asked in these information studies can include:

- What was the size, shape and distribution of their nuclear programme?
- Was any one nuclear weaponisation pathway prioritised over another?[1]
- Which relevant facilities/capacities were pursued, when, and in what geographical distribution?
- What was their approach to transparency?
- Did they misuse declared facilities for undeclared processes?
- Did they pursue a clandestine parallel programme?
- Were all of their nuclear activities clandestine?
- How did their geopolitical situation affect their decision to pursue nuclear weapons?

- How did their geopolitical situation affect the technical shape of their proliferation efforts?
- Were there any notable changes in approach, in response to successes/failures?
- While they existed as a nuclear state, were there any notable changes in approach in response to successes/failures that influenced the decision to abandon (or not to abandon) their nuclear efforts?
- To what extent did multilateral/bilateral agreements control the abandonment of their efforts (where relevant)?
- Who was involved in these agreements?
- How were they negotiated?
- How detailed were these agreements, and to what extent did they specify verification requirements?

By identifying themes and characteristics, this information gathering can be used to inform a broad idea of how each modelled state's nuclear complex should look like. It can help establish a fictional geopolitical history for each modelled scenario—the state's political identity and its relationship with the international community and the non-proliferation regime in particular—as well as its scientific and technological sophistication—the size of its industries, its nuclear ambitions, and its approach to developing nuclear technology and weapons.

From here, it is possible to draw-up an initial image of the fictional state's nuclear fuel cycle and the constituent 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 or whether the same facilities have been employed both for civilian use and for the production of material for nuclear weapons. The answer to this question dictates how the modelled state will behave and the types of technologies it will develop. This is further dependent on the modelled state's access to source material and on whether or not it imports or mines uranium indigenously.

Stage 2—fissile material demand

In this stage, key questions concerning the modelled state's nuclear weapons programme are addressed in order to establish a target for guiding the construction of a fictitious background history. This involves deciding on the final number of weapons that will comprise the state's nuclear arsenal, the arsenal's diversity (whether it will consist of one or more weapon classes), composition (whether the weapon cores are made of uranium, plutonium or both), as well as the number of nuclear weapons tests performed for each weapon class and the amount of fissile material consumed in each test. In addition to providing an end-point for the state's background history, this process also provides data relating to the breadth and sensitivity of the state's nuclear weapons programme, which is crucial information for the simulation exercises.

Stage 3—devising a background history

Once the modelled state has been given a suitable profile and a final number of nuclear weapons (plus nuclear explosive tests) and thus a fissile material demand, it becomes possible to devise a background history for the development of its nuclear programme.

This involves projecting backwards, from the present time, the number of years needed to achieve the target weapons and material production for the modelled state. If the model represents a sophisticated nuclear weapons programme, for example, with many thousands of weapons, then it will take an appropriate length of time 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. T0 represents the point where one can begin studying the verification of disarmament drawdown of nuclear material from warheads and weapons stockpiles.

In order to ensure that each facility in the model's timeline is credible, both in terms of the historical accuracy for the technologies it uses and for 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 fissile material to pass through the facility?

Devising the timeline is an end-focused activity. It requires researchers to constantly balance facility construction and operations with sufficient material production in order to satisfy material demand for the weapons programme.

For each facility in the timeline, additional desk-based research should be conducted to ensure that it is equipped with appropriate technologies for the historical time that it is operating. There is little value in having a model that includes present day technologies that are inappropriate for earlier decades—anachronisms undermine the model's value. In addition, this research should build individual profiles for each facility in the fuel cycle. These profiles include details on that facility's specific operating conditions and properties. For example, if the state is developing enrichment capabilities, will it choose gas centrifuges? Which centrifuge design will it use and how many centrifuges will it house? What then is the enrichment plant's capacity and what fraction of that capacity does it manage to reach? When did it come on stream and when does it cease operations? What is its annual feed requirement?

Or, 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 reactor. How long will fuel stay in the reactor, what is the downtime versus operating time and what is the maximum burnup for each irradiation cycle? The answers to these questions are fundamental for setting up the conditions for generating realistic output data from the model.

The process for establishing the timeline and plotting the operating dates for each facility in the modelled fuel cycle, in each worked example, entails balancing material requirements with the time it takes for a given fuel cycle process to be completed. For instance, if the state developed its own nuclear facilities and utilised indigenous uranium ore supplies, then the model will require mass transfer elements (single, fixed locations at which fissile material mass is tallied, used in the mathematical calculations for 'updating' a fissile material inventory as time passes in the modelling) representing mines and mills.

The timeline will need to take into account the number of months or years it takes to design and build these facilities, and to exploit the uranium deposits so that sufficient quantities of uranium has accumulated to feed the 'conversion' process (changing uranium oxide to uranium hexafluoride). The time this takes is dependent on the model's assumptions about the size and nature of its mine(s), and how rich the uranium deposit is.

If the imagined state does not have access to uranium mines, then it may import stocks of U_3O_8 to feed its nuclear programme. This could shorten the timeline by a few years. If so, then the first facility to enter into operations could be a conversion plant for producing uranium hexafluoride to feed an enrichment plant (if the state is utilising LEU fuel) and then a fuel fabrication plant.

This process could take a year or two to complete before fuel is ready for the nuclear reactor, especially if it uses a large core. In constructing the fictitious timeline for our example countries, it was found best, in practice, to decide on the start-up date for the reactors first. It was easier to work backwards from there in order to plot the rest of the timeline, as this provided a fixed date for when a specific amount of fuel needs to be created.

An example can be seen in Figure 2 below, which shows the timeline for 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 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).

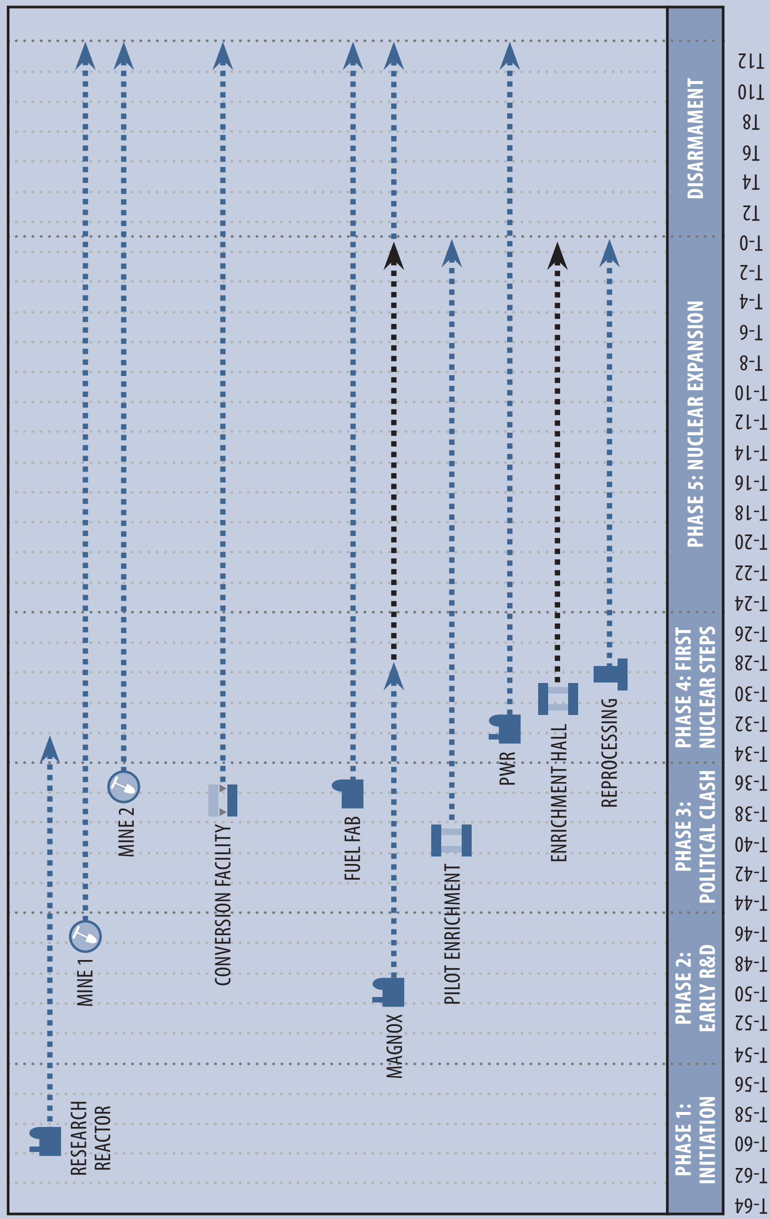


Figure 2 Timeline for construction of Example Country 2's nuclear complex

Stage 4—data generation

When generating information for nuclear fuel cycle models, a number of prerequisites need to be taken into account. Principally, there should be a clear understanding of what the model's purpose is and what type of information is needed to achieve it. As highlighted above, the process of building the model's timeline needs to be end-focused; the same is true for data collection. Without a clear understanding of what the purpose is, the model could be overloaded with superfluous information limiting its usefulness. Moreover, although many features of the civilian fuel cycle are well documented in open-source literature, the same cannot be said for military programmes and the details surrounding weapons production. Information for these processes is 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 nuclear warhead component is fraught with challenges.

Researchers developing a comprehensive model of a notional nuclear weapon state therefore have to negotiate between two extremes: on the one hand sifting through and selecting from a glut information on nuclear fuel cycles, and, on the other, contending with the paucity of information on weapons production and their material requirements.

When it comes to modelling civilian fuel cycle activities, simplicity should be the guiding principle: a model often derives its power from its ability to simplify its treatment of a process or phenomenon. It is therefore important for researchers to make key decisions on what information is essential to the model's purpose and what is additional or just nice to have. For the purpose of providing baseline data for disarmament verification simulations, the focus of data generation is fixed on the production of fissile material, fractional loses in any particular process, and logging fissile material holdings at specified locations, for the modelled programme's entire history. The model is therefore driven by capturing information for all stages of the fuel cycle and accounting for stocks of source material as they progress through the various chemical and nuclear processes in each facility, as well as those facilities' individual operating conditions.

The process for populating the model with data for fissile material production can be seen as a continuation of the timeline activity described above. Once the timeline has been established and is complete with all facilities, their individual start-up times, capacities, feed requirements and specifications, further research can be conducted into material production—this information will form the data for each facility.

There are multiple options available for generating this information depending on the type of state that has been chosen for the model. Obtaining information on the annual production capacities of most fuel cycle facilities is not difficult. There is an abundance of open-access resources and textbooks available that provide detailed descriptions and technical instruction for each stage of the nuclear fuel cycle, their operating conditions as well as calculations for estimating material production.[2] More specifically, significant scholarship has gone into reconstructing the technical histories of the existing nuclear weapons states. These resources can be used to piece together details for facility capacities and for annual material production.

Additionally, a number of potentially useful software packages exist that generate quantitative data for all or specific parts of a modelled fuel cycle. ORIGEN-ARP, developed by Oak Ridge National Laboratory, is one such piece of software that can model the production and consumption of nuclides as a function of time. ORIGEN-ARP can provide precise data for plutonium production in reactor fuel for both civilian and military reactors (the changing variable being the neutron flux and the length of time that the fuel stays within the reactor). For example, if the reactor being modelled is generating electricity for a civilian nuclear programme, then users can optimise the burnup to an appropriate level in order to maximise fission within a given reactor core load. Alternatively, users can lower the maximum burnup for the fuel and therefore produce plutonium that is better suited for weapons use.[3]

When it comes to modelling classified processes such as those involved in the weaponisation process, researchers must rely on approximated figures for various activities. 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.[4] 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 will become more efficient over time and require less material.

Estimation sacrifices accuracy, but it does provide data that can be used in modelling and allows researchers to bypass certain issues associated with proliferative information that might be contained in open-source documents that speculate on how nuclear weapons are built.[5] Within the simulation exercise, reasonably approximated information can still be useful as long as the model is internally consistent.

This is crucial for modelling the individual processes involved in manufacturing weapons within a weapons complex. In this instance, not only are details about the weapons classified, but so are 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, undergo a series of unspecified processes that then produce a final output product—a nuclear weapon with a pit consisting of an approximated quantity of fissile material. In this case, a researcher can assume that production process will result in a degree of material loss as the fissile material is shaped and machined to form the 'pit'—in the case of an implosion device. It is therefore possible to apply a standard loss fraction for this process and to record the estimated loss for each year of operations.

Facility sheets

In addition to the plotted timeline, each model can include a set of datasheets that represent fissile material inventories in each facility in the example country's nuclear programme—for both civilian and military fuel cycles, where relevant. These facility sheets are divided into three portions that account for the facility's input, operating process and its output for every year in the model's fictional timeline. So, for example, 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 portions are then subdivided into columns that contain space for recording data on specific processes and the quantities of material (all measured in kilograms).

Once complete, the facility sheets contain quantitative information for the following:

- Facility type, and the year when it came online;
- The facility's operating conditions, properties and capacities[6] (for example, reactor burnup, maximum core load, thermal power or centrifuge separative work unit);[7]
- Quantities of material before, during and after a given process;
- Quantities of a specific isotopes of interest (^{235}U and ^{239}Pu) before, during and after a given process;
- Cumulative material in facility before, during and after a given process;
- Quantities of material being dispatched from a facility;
- Shut-down or refuelling periods;
- Loss factors for specific processes (for example, material lost during conversion of U_3O_8 to UF_6, fissile material loss during weaponisation processes);
- Tails or waste quantities.

Once collected together, the data in these tables form a material account for all facilities throughout the state's fictitious development history.

The following section will provide an overview of Example Country 2 which is the fully developed model developed under VERTIC's MVND project. Example Country 2 will serve as an example to highlight the various stages and features that constitute the final model timeline, fuel cycle facilities and some of the respective operating conditions. It should be noted that this is not an exhaustive example of all of the data contained within the Example Country 2 model, but just example features.

Worked example—Example Country 2

Example Country 2, its nuclear history and types of facility

Example Country 2 was originally designed to resemble a nascent nuclear weapon state whose fuel cycle was employed for both civilian and military purposes. The state was envisaged as having a small arsenal of 50–60 nuclear weapons by T0, at the point where it agrees to disarm. In essence, Example Country 2 is intended to resemble aspects of an actual country's nuclear programme—DPRK, which is of topical concern—so that the disarmament simulation can explore hypothetical challenges that might be presented by any future disarmament arrangement with that country.

1950s—initiation phase

In the 1950s, Example Country 2 obtained a research reactor through foreign assistance and development programmes. This facility was placed under item-specific safeguards (INFCIRC/66), and the spent fuel was sent back to the supplying country for reprocessing.

1960s—early R&D phase

In the mid-1960s, Example Country 2 was provided with two small 25 Megawatt thermal (MWth) gas-cooled, graphite moderated, Magnox reactors, which were used for generating electricity. Like the research reactor before them, this Magnox reactor was placed under IAEA item-specific safeguards, and the supplying country provided fresh fuel and retrieved it as spent fuel once it had been used in the reactors. The fuel for the reactor was irradiated (that is – used) for four years per cycle and reached a maximum burn-up of 700 Megawatt days per tonne.

During this time, Example Country 2 launched R&D programmes covering uranium conversion, enrichment, fuel fabrication, and spent fuel reprocessing as well as research into their own pressurised-water reactor (PWR) design for civilian power generation purposes.

1970s—political clash

Throughout the 1970s, Example Country 2 began operating key fuel cycle facilities: it began stockpiling indigenously mined uranium ore from its two large uranium deposits; it started converting and fabricating natural uranium fuel for its Magnox reactor while also producing low enriched uranium (at 3.03 per cent ^{235}U) for its PWR at a pilot enrichment plant (using centrifuges similar in design to URENCO G2 centrifuges). The fuel for both reactors was tested in the old research reactor. At the end of the decade, Example Country 2 took the final decision to develop nuclear weapons.

1980s onwards—steps to nuclear weapons

In the 1980s, the results of Example Country 2's nuclear research over the previous 20 years came to fruition. It launched a full-scale enrichment plant, its indigenously developed PWR and a spent fuel reprocessing facility. The enrichment plant began producing 90 per cent highly enriched uranium (HEU) to be used in its first generation of nuclear weapons. By 1991, Example Country 2 had produced 572.9 kg of HEU for its weapons programme.

By the end of the decade, Example Country 2 started using its own indigenously produced Magnox reactor fuel, as the fuel supply agreement it had originally stipulated came to an end. After introducing its own fuel, Example Country 2 ran the Magnox reactors to a lower burn-up compared to the previous irradiation cycles (from 700 Megawatt days per tonne to 160 Megawatt days per tonne), and refuelled it more frequently, once a year. This resulted in Example Country 2 producing approximately 8 kilogrammes of weapons-grade plutonium (97-98 per cent ^{239}Pu) with every irradiation cycle.

While initially Example Country 2's leadership thought that its own domestic PWR could be used for weapon-grade plutonium production as well, obtaining irradiated material of a sufficiently similar isotopic composition to be used in conjunction with the plutonium recovered from Magnox fuel proved to be difficult, and the PWR was eventually dedicated to civilian use only.

Example Country 1—an overview of its nuclear history and the types of facility modelled

Chronologically, the MVND project's first worked example was 'Example Country 1'—a medium-sized nuclear weapons state with two distinct fuel cycles—one dedicated to civilian power generation and the other dedicated to military activities. Prior to the decision to disarm, Example Country 1 was equipped with a medium-sized and modern nuclear arsenal of a few hundred ballistic missiles launched with two-stage nuclear warheads, a retired arsenal of gravity bombs as well as three nuclear propelled naval vessels. The disarmament scenario attached to this model dictated that Example Country 1 would enter into an agreement to disarm all of its nuclear weapons in a hypothetical multilateral disarmament situation, alongside all other nuclear weapons-owning states. Example Country 1 was imagined as an NPT Nuclear Weapon State, with a nuclear history dating from the mid 1950s.

Example Country 1 developed a small, but geopolitically significant nuclear arsenal by To when the multilateral disarmament situation started. The state had to rely on imports of U^3O^8 to fuel both its nuclear fuel cycles, as it did not have indigenous uranium deposits to utilise. Using the United Kingdom as inspiration, a decision was made to furnish the model with gas-cooled, graphite moderated Magnox reactors to be used for producing Example Country 1's weapons-grade plutonium. In order to prevent the model from completely resembling the United Kingdom, Example Country 1's civilian programme used pressurised water reactors that are similar in design to the Russian VVER-440s.

To keep the modelling simple, we chose not to mix military and civilian operations in the same facilities. Thus Example Country 1 does represent a slightly idealised and simplified picture, where discrete process lines are followed—from source material conversion, via enrichment, fuel fabrication, reactor operation, to reprocessing and plutonium product storage—in a dedicated civilian plant or a dedicated military plant. Although this has not been the case for many real-world nuclear states, it was seen as the best first option for this demonstration study. Example Country 1 is currently being updated to match the sophistication of Example Country 2. In addition, an important follow-on activity would be to complete a model that represents a large-scale nuclear programme that is similar to those of the US and Russia. This model could be matched with a scenario that involves a reciprocal disarmament agreement, with multilateral verification in operation.

Conclusion

The models developed under VERTIC's Multilateral Verification of Nuclear Disarmament Project are intended to provide quantitative data for fictitious nuclear weapon states that serve as a basis for conducting simulation exercises with selected disarmament verification scenarios. These models contain detailed information on the quantity of fissile material, number of warheads and related components in inventories for all parts of the fuel cycle. The information contained within each model can serve as baseline information for conducting tabletop or live play exercises for investigating verification solutions for a wide range of multilateral disarmament scenarios. They allow simulation players and control teams to identify unexpected verification challenges for specific facilities, to investigate and devise new approaches to overcoming these challenges, and to prepare future inspection teams for hitherto under-explored scenarios.

A useful next step for the modelled data described in this chapter is to use it as the basis for a tabletop negotiation simulation exercise whose overall objective is to devise a notional disarmament verification agreement between Example Country 2 and its neighbours. Within this exercise, Example Country 2 will agree to disarm its nuclear weapons programme and weapons stockpile and to place all of its military facilities under IAEA safeguards. The exercise will use the data to identify the technologies and procedures that might be needed to verify correctness and completeness of fissile materials emerging from Example Country 2's military programmes. These negotiations can explore the access and the degree of measurement intrusiveness that would be required by inspectors—and what would be tolerable to nuclear facility management in a disarming state.

In so doing, this type of simulation will aim to add to current debates on future non-proliferation and arms control verification activities, and can be used to help train and educate future inspection teams, students and professionals involved or interested in nuclear disarmament verification and non-proliferation studies.

While the worked-example simulations described here focus on the dismantlement of nuclear weapons and the safeguarded storage of special fissionable materials, these simulations could be carried out for quite different scenarios. For instance the methodology could be used to examine cases in which military programmes are merely scaled down, restrained, or only parts are discontinued, facilities converted to civilian use or otherwise decommissioned, or the safeguarding of previously undeclared activities or material, or broader constraints on nuclear activities.

The methodology developed could also be used to model expansion of weaponisation in real states, and to assess the impact on proliferation risk of expansion in civilian nuclear programmes.

Endnotes

1 For a description of the two routes to making a nuclear weapon, see chapter 2 in this volume 'Securing the front end of Iran's fuel cycle' by Andreas Persbo and Hugh Chalmers.

2 For a general overview of many aspects of the fuel cycle, see 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.

3 The reason for this difference is that the higher the neutron fluency (the final burnup), the larger the proportion of the higher plutonium isotopes (^{240}Pu, ^{241}Pu and ^{242}Pu) builds up in the fuel. The most desirable isotope for nuclear weapons is ^{239}Pu. ^{241}Pu is fissile, but has a short half-life of 14 years (it decays into americium-241), which is an intense emitter of X-rays and gamma rays as well as producing 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 considerable amount of heat. The neutrons emitted in this fission process increase the likelihood that the chain reaction in a bomb will begin before full compression of the plutonium has been achieved—causing pre-detonation.

4 The IAEA currently defines a significant quantity as 'the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.' For plutonium it is 8kg (for plutonium containing less than 80 per cent ^{238}Pu), and 25kg of ^{235}U in HEU.

5 See Richard Rhodes, 1986. *The Making of the Atomic Bomb* (New York: Simon & Schuster) and *Dark Sun: The Making of the Hydrogen Bomb* (New York: Simon & Schuster); Chuck Hansen, 1988. *US Nuclear Weapons: The Secret History* (Aerofax) and 'The Swords of Armageddon': www.uscoldwar.com/

6 Investigations into facility properties, optimal operating conditions and capacities were conducted as part of Stage 3 of the modelling process.

7 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). For more information, see www.world-nuclear.org/info/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment/