Nuclear Disarmament Verification Concepts for the Disposition of Special Nuclear Material

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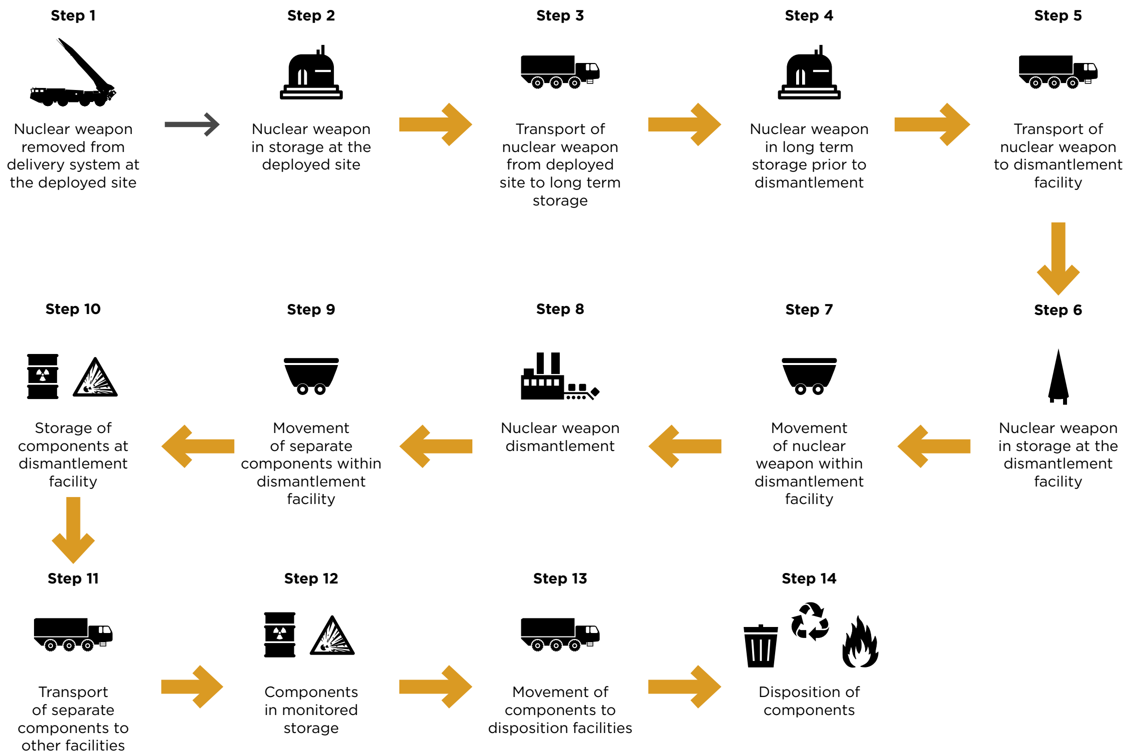
Introduction

The International Partnership for Nuclear Disarmament Verification (IPNDV) has considered technical solutions for the dismantlement of nuclear warheads. A schematic visualization of the dismantlement flow was developed early in the first phase of the Partnership's work. Referred to as the "14-steps," this model (Figure 1) has proven useful in this work.

Figure 1: The IPNDV 14 Steps for Nuclear Dismantlement



During earlier work in the IPNDV, Steps 1–13 were considered in detail, both with regard to the flow of a single nuclear warhead as well as the dismantlement of many nuclear warheads over extended time periods.

Although verification of the disposition of nuclear warhead components (Step 14) was discussed to some extent in these earlier phases of IPNDV, it was not considered in any detail until this current phase. Under one proposed approach, the disposition of the special nuclear material (SNM) components from dismantled nuclear warheads would be altered into objects that have no, or at least fewer, proliferation-sensitive properties and are not directly usable to produce new nuclear warheads. This approach to Step 14 would involve some physical and/or chemical processing of those components. Up until Step 14, the nuclear warheads in Steps 1–7 and/or their components in Steps 9–13, are in principle directly usable for nuclear weapons. Thus, the approach to Step 14 being discussed in this paper would involve a more elaborate procedure than the previous steps. (For the rest of the paper, we assume that the approach to Step 14 involves the processing and alteration of the SNM components).

At the same time, Steps 8 and 14 are arguably the most important steps in the entire dismantlement process. In Step 8 the nuclear warhead is disassembled and separated into components (e.g., SNM and high explosives) rendering it unusable as a weapon without further processing. In Step 14 the components are physically altered rendering them permanently unusable for nuclear weapons without significant re-modification. Although the other steps in the process are important for verification, they do not alter the characteristics of the treaty accountable items.

In principle, several or all the different kinds of components could be covered by verification during Step 14. Although one could argue that all different forms of components should be disposed of in a verifiable manner, we have focused on the fissile material components given that nuclear material control and accounting plays a key role in nonproliferation more broadly.

One of the inherent complexities of both Step 8 and Step 14 is for the inspectors to have confidence that the host party is abiding by its treaty obligations while at the same time protecting proliferation-sensitive information as well as complying with all safety and security concerns. Of course, these complexities are relevant in all steps, but become more challenging when treaty accountable items change their characteristics.

In addition, Step 14 has some unique aspects that are not found upstream in the previous 13 steps. First, this is a step where the verification changes from an item-based approach, that is, with discrete numbers and identities of warheads or components to a flow of fissile material. Second, the disposition may require that the treaty accountable nuclear material is blended with other similar fissile material in order to produce an isotopic and chemical material form that is suitable for the disposition end-state. Furthermore, to avoid any means of calculating the precise fissile masses or isotopic compositions of the original treaty accountable component material, limited declarations may exist for blending material mass and composition. Hence, for blending of the component material, it is not only components that enter Step 14 but potentially other blending nuclear material.

Other methods could be applicable to Step 14 without using any mixing material and subsequent blending. For instance, the physical characteristics of the material could be changed, for example, from a solid component to a powder, and then be vitrified for long-term monitored storage. In this paper we will confine ourselves to Step 14 methods that at least in principle render the output available for detailed inspection under a safeguards-like process. This implies that the host state that performs the blending of fissile material has a legal but undeclared stock of fissile material. However, after Step 14, both the amount of fissile material from the components as well as the amount of blendstock will be part of that state's declared stock.

Generic Process Description

Step 14 aims to maintain chain of custody of components and ensure the integrity of the disposition process. Monitoring/inspection activities to maintain the chain of custody and containment and surveillance procedures must be used to ensure that these components securely arrive at the disposition facility and prior to their actual final disposition. Multiple options exist for final disposition of these components, including transfers to permitted military use, civilian use, and/or storage and disposal. Final disposition processes could include chemical processing and downblending of the SNM, using the following technical procedures:

- SNM components are transported to disposition facilities.

- The SNM is processed into a chemical form suitable for subsequent processing.
    - For example, under the U.S.-Russia Highly Enriched Uranium (HEU) Purchase Agreement, metallic HEU from nuclear warheads was machined into shavings, which were converted into an oxide, and then into uranium hexafluoride in a third process step.
- The SNM may be mixed with a second material stream so that the final isotopic mixture is suitable for final disposition.
    - Natural, depleted, or low enriched uranium (LEU) are suitable blending materials for HEU.[1] Reactor-grade plutonium is a suitable blending material for plutonium.
    - This process may also reduce sensitive characteristics in the resulting product.
- Material may be stored in between processing steps, which may involve moving containerized material to a separate, dedicated storage area.
- Final disposal might involve additional steps to sanitize any sensitive characteristics.
- The product is disposed, either through permitted military use, civilian use, and/or storage and disposal.

A schematic flow chart of these process steps is shown in Figure 2.

As was discussed in the introduction, the major conceptual difference between Step 14 and the previous steps centers on the fact that Steps 1–13 are item-based—the individual warheads and their components after dismantlement—and verification concepts focus on tracking their movement through the disarmament process. In Step 14, however, the potential to perform material processing alters an SNM component's chemical form, enrichment, and geometry; notably discrete SNM components are transformed to bulk material, which has implications for how verification is performed that are unique to this step.

Figure 2: Flow Chart of the Major Process Steps Involved in Step 14 of the Dismantlement Model

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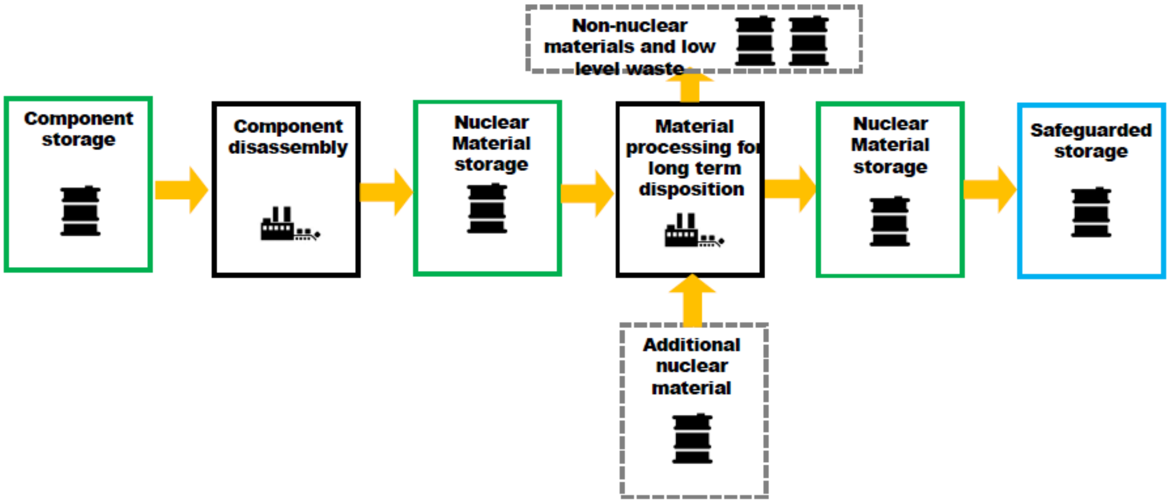
[1] The intended use of the final product may dictate the properties of the blending material. For example, if the downblended material is to be used as reactor fuel, fuel standard limitations on the concentration of ^{234}U require slightly enriched uranium as blending material.



Although the disposition processes for HEU and plutonium are similar in principle, they differ considerably in terms of their technical implementation. First, uranium and plutonium have unique chemical properties and different chemical forms suitable for downblending. Second, plutonium and HEU might require very different blending ratios to meet final disposition requirements. Due to these differences, different disposition facilities might be required for processing the HEU and the plutonium.

The potential for material processing as part of final disposition has another implication that needs to be taken into account in developing a verification concept. Every material processing step will inevitably result in material loss through waste streams or with material held up in process lines, complicating the material balance across the facility. Plant operators will use specialized processes and equipment to minimize material losses, avoid criticality risk, and limit occupational radiation exposures. This is particularly important for plutonium, given its low critical mass and high dose rate. Additionally, SNM held up in process lines will increase the radiation background, potentially affecting verification systems. Figure 3 shows an example of connected gloveboxes used to address such concerns related to plutonium processing.

Figure 3: An Example of Connected Gloveboxes[2]

A Verification Concept for SNM Disposition with Alteration of SNM Components

Approach and Major Verification Activities

In its analysis of the disposition approach set out in this paper, the IPNDV developed a concept using a methodology whereby the verification requirements of Step 14 are compared with those of Step 8, to identify differences and to develop appropriate verification procedures that address those differences. This approach has been chosen because, first, the Step 8 verification approach has been successfully tested by IPNDV in various tabletop exercises and the two full-scope in-person exercises (NuDiVe).[3] Second, Steps 8 and 14 share some of the proliferation concerns that have to be taken into account when designing the verification approach.

The Step 8 verification concept is based on the procedures developed for and successfully tested in the NuDiVe exercises with some minor modifications to generalize specific NuDiVe scenario

[2] Michael E. Cournoyer, Julio M. Castro, Michelle B. Lee, Cindy M. Lawton, Young Ho Park, Roy Lee, and Stephen Schreiber, "Elements of a Glovebox Glove Integrity Program," *Journal of Chemical Health & Safety* 16, no. 1 (2009): 4–10, https://doi.org/10.1016/j.jchas.2008.03.001.

[3] The Franco-German NuDiVe documentation and evaluation reports are available at https://www.ipndv.org/?s=NuDiVe.

assumptions. It is based on the general strategy of treating the dismantlement process as a black box and verifying by perimeter monitoring combined with absence measurements that no unaccounted fissile material enters or leaves the process area.

The disposition of the treaty accountable SNM components in Step 14 shows the following conceptual differences to dismantlement (Step 8):

- Disposition may include material processing and blending that alters an SNM component's chemical form, enrichment, mass, and geometry.
- As part of disposition, material processing might include the addition of non-treaty accountable nuclear material.
- The disposition process might involve a transition from discrete item tracking to continuous material processing.
- The disposition process might include steps to sanitize sensitive information of the input components.
- Measurable attributes of the SNM components involved in prior steps might not be directly applicable to treaty accountable bulk material in Step 14, particularly if final disposition involves significant material or chemical processing.
- Material accountancy is further complicated when additional waste streams from chemical processing steps need to be considered.

Similar to the NuDiVe Step 8 approach, the Step 14 verification concept detailed below considers the disposition process as a black box and relies on perimeter monitoring combined with absence measurements to verify that no unaccounted fissile material leaves the process area.

In the following, it is assumed that both Step 8 and Step 14 process work is carried out in facilities that have ongoing nuclear weapons maintenance activities taking place.[4] During periods when such work is performed, verification equipment and inspectors must be absent. This results in additional verification procedures that would not be required in the case of facilities dedicated to treaty-specific processing because such an area could be permanently installed with monitoring equipment and chain of custody measures.[5] Additional verification procedures required in non-dedicated facilities are noted for each activity below.

Another assumption underlying the verification approach described below is the assumption that inspectors have access to the process area between disposition activities for visual inspection and application of verification technologies. Without such access rights, the verification approach would have to be modified and instead rely to an even larger extent on perimeter monitoring.

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[4] At some point in a reductions (elimination) scenario, this might no longer be necessary.

[5] See IPNDV, Conceptual Elements of Potential Verification Strategies, 2025.

1. Arrival and Briefing

Step 8:

- The inspectors arrive onsite and are led into their working rooms. After receiving safety instructions, a briefing with the host will establish the next steps.
- In the dedicated disposition area, if a team of inspectors is present at all times, personnel will be periodically rotated.

Step 14:

- No conceptual or technical differences have been identified.

2. Installation of Perimeter Monitoring and Detector Technologies

Step 8:

- The perimeter monitoring equipment, for example, Closed Circuit TV (CCTV) surveillance system and portal monitors, is retrieved from sealed containers and installed.
- In a dedicated disposition area, this equipment may be installed permanently.

Step 14:

- No conceptual or technical differences have been identified.

3. Inspection of Dedicated Dismantlement/Disposition Area

Step 8:

- The dedicated dismantlement area is inspected to confirm its configuration against the site diagrams. All potential diversion pathways are identified and sealed as appropriate. If seals are present from previous inspections, their integrity is verified.
- The area is inspected using radiation detectors (handheld and imaging) to ensure the absence of fissile material, which could be used for swapping with warhead SNM components.

Step 14:

- The use of radiation detection equipment to ensure the absence of fissile material would not be applicable if the dedicated disposition area includes non-treaty accountable material intended to be mixed with the treaty accountable SNM. Additionally, due to possible remaining contamination and/or hold-up of fissile material from earlier processing activities, it would also in practice be impossible or severely restricted.
- In a dedicated disposition area, visual inspections can be limited to verifying the integrity of the applied seals during process breaks.

4. Arrival of the Treaty Accountable Items (Nuclear Warhead in Step 8/Separated SNM in Step 14)

Step 8:

- The containerized warhead arrives in the dismantlement area and tags and seals are checked to maintain chain of custody. The warhead may undergo non-destructive assay to confirm presence by measurement using an information barrier. The container is moved into the dedicated dismantlement area. On the way, the portal monitor confirms the presence of fissile material. From this point onward, an inspector is present at the entrance/exit of the dedicated dismantlement area at all times.

Step 14:

- No conceptual or technical differences have been identified.

5. Inspection of Containers with Non-accountable Items and Equipment

Step 8:

- Although nuclear warhead dismantlement is a mechanical process, it will require some consumables. Containers with these materials are transported into the dismantlement area. The portal monitor confirms the absence of fissile material, which could be used for swapping with warhead SNM components.

Step 14:

- This activity can be skipped if material processing includes addition of non-treaty accountable nuclear blending material during the disposition operations. Containers of blending materials may only have limited inspections in order to reduce sensitive information in the final product.

6. Inspection of Empty Containers

Step 8:

- The empty containers for the nuclear and non-nuclear components resulting from dismantlement of the nuclear warhead are transported into the dismantlement area. The portal monitor confirms the absence of fissile material.

Step 14:

- Portal monitoring to confirm the absence of fissile material can be skipped if material processing includes the addition of non-treaty accountable nuclear material. However, Step 14 does require an accurate inventory of containers entering and leaving the dedicated disposition area; with access to the process area between disposition activities, such an inventory would be more straightforward.

7. Active Dismantlement/Disposition Operations

Step 8:

- The door of the dedicated dismantlement area is closed, and the dismantlement operations commence. This process is expected to take up to two weeks. The inspectors stationed outside the room will screen any personnel entering or leaving. When the operations pause overnight, the inspectors need to leave and the area is sealed until the inspectors return and the dismantlement operation is resumed.

Step 14:

- No conceptual differences have been identified. Although the disposition process is characterized by a continuous flow of material, it could be organized in sets of activities with breaks that allow for inspection of the dedicated disposition area to confirm no diversion pathways have been developed (see also 13 below).

8. Re-Establishment of the Chain of Custody on Resulting Materials

Step 8:

- After dismantlement, the inspectors tag and seal the containers of the separated SNM and high explosive components.

Step 14:

- No conceptual or technical differences have been identified, except that only fissile material is considered in Step 14.

9. Exit of the Fissile Material Container

Step 8:

- The container housing the SNM is transported to a non-destructive assay room. The portal monitor confirms the presence of radiation on the way, and a non-destructive assay measurement confirms that the radiation signature corresponds to the nuclear warhead component. After tagging and sealing the container and providing it with a unique identifier, the SNM container is transported onward.

Step 14:

- The potential for an unknown input stream increases the importance of post-process verification steps.

- As a result of the disposition process, the material has changed form and may have been sanitized of sensitive characteristics, which would alter the verification strategy and may allow containers to be analyzed in more detail.
- As part of disposition, if material processing includes the addition of non-treaty accountable nuclear material, verification steps may be needed to have confidence that SNM components were processed. For example, verifying that isotopic ratios do not exceed a defined threshold could provide additional confidence that the accountable SNM is part of the blended output.

10. Exit of the Empty Nuclear Warhead Container (Step 8)/SNM Component Container (Step 14)

Step 8:

- The empty nuclear warhead container is transported to the non-destructive assay room, and non-destructive assay is performed.[6] Afterward, it is transferred onward.

Step 14:

- No conceptual or technical differences have been identified. The potential for an unknown input stream increases the importance of verification that the original SNM components are, in fact, processed and not removed.

11. Exit of the Non-Accountable Containers

Step 8:

- The non-accountable containers undergo the same procedure as in inspection activity 10.

Step 14:

- As part of disposition, non-accountable containers might contain fissile material—either unconsumed bulk material or trace concentrations in waste streams. Therefore, processes and definitions for distinguishing treaty accountable materials and non-treaty accountable materials may need to be established (e.g., alarm thresholds for absence measurements to verify that waste contains less than a minimum threshold of nuclear material). This will likely affect the techniques used to confirm absence.

[6] This approach will also be used to verify the absence of fissile material in the high explosives container.

12. Re-Inspection of Dedicated Dismantlement/Disposition Areas

Step 8:

- After dismantlement of a nuclear warhead is complete, the dedicated dismantlement area is inspected to confirm the absence of fissile material. All seals attached to potential diversion pathways are checked and documented.

Step 14:

- After a disposition activity is completed, the dedicated disposition area is inspected to confirm the absence of fissile material and the presence and integrity of the applied seals.
- The dedicated disposition area might include fissile material, either unconsumed bulk material or process hold-up. Absence measurements may need to verify that waste contains less than a minimum threshold of nuclear material. This will likely affect the techniques used to confirm absence.

13. Removal of Perimeter Monitoring Technologies

Step 8:

- In case of a non-dedicated area, CCTV footage is retrieved. CCTV and portal monitors are removed and sealed for storage ahead of the next inspection, if the area will be used by the host afterward for non-treaty related activities.
- This activity is not required in a dedicated dismantlement facility/area.

Step 14:

- No conceptual or technical differences have been identified.

14. Optional Procedures Specific for Step 14

- The potential for final disposition to include significant material and chemical processing could result in material from treaty accountable items being held up within processing lines and therefore complicate the material balance within the disposition area. Additionally, the total mass entering or leaving the disposition area might be deemed sensitive.
- One potential solution would be to disclose to inspectors only the difference between the amount entering and leaving a verification unit. This could be particularly useful if the total mass entering or leaving the disposition area is deemed sensitive or if any processing areas do not permit inspectors to enter.
- Mass flow measurements could be particularly useful if inspectors do not have access to the dedicated disposition area or parts of it.

Applicability to Highly Enriched Uranium

A major historical precedent for the disposition and verification of HEU is the 1993 U.S.-Russian HEU Purchase Agreement, commonly known as the “Megatons to Megawatts” program. Under this bilateral agreement, Russia committed to down blend 500 metric tons of weapons-grade HEU (nominally 90 percent ^{235}U), extracted from dismantled nuclear warheads, into LEU for use as commercial reactor fuel in the United States.

The HEU Transparency Program established an inspection and monitoring regime across several Russian and U.S. nuclear processing facilities, including:

- **Mayak Production Association (MPA)** and **Siberian Chemical Enterprise (SChE) Chemical-Metallurgical Plant**: Received HEU components from nuclear weapons dismantlement sites and converted HEU metal into purified oxide.
- **Electro Chemical Plant (ECP), SChE,** and **Ural Electrochemical Integrated Plant (UEIP)**: Processed HEU oxide into uranium hexafluoride (UF_6) and performed the downblending to LEU.
- **U.S. Facilities:** The Paducah Gaseous Diffusion Plant received the LEU for further processing and sent material on to other U.S. facilities for fuel fabrication. The fuel fabrication facilities included Westinghouse, Global Nuclear Fuels, and AREVA.

Transparency monitoring included both periodic Special Monitoring Visits (SMVs) and a permanent Transparency Monitoring Office (TMO) to provide continuous oversight at key processing facilities.

Both the HEU Transparency Agreement and the IPNDV Step 14 process described previously share the core objective of transforming classified HEU derived from nuclear weapons into a form that is no longer suitable for weapons use and is permanently removed from the weapons program. Just as shown in Figure 2, the process involves:

- **Item-to-bulk transition:** Classified warhead components (items) are verified upon entry into the process, then converted into bulk chemical forms (e.g., metal shavings, oxide, then UF_6).
- **Destruction of sensitive geometry:** The metallic HEU is physically and chemically transformed, eliminating classified shapes and characteristics.
- **Blending with other uranium streams:** The HEU is mixed with slightly enriched uranium to achieve LEU suitable for reactor fuel.

However, there are some notable differences:

- **Chain of Custody:** Items entering the Step 14 process will likely have chain of custody and a history of previous inspections from previous steps; in the HEU Transparency Program such items did not have a previous inspection history with HEU items entering the process, and included host-applied seals and reviewed redacted shipping documentation to confirm the origin and quality of incoming material.

- **Verification Approach:** The Step 14 concept emphasizes perimeter monitoring and absence measurements; these were not part of the verification approach in the HEU transparency inspections.

- **Agreement Partners:** The HEU Transparency Agreement was an agreement between two nuclear-weapon states (NWS) and did not include any non–nuclear-weapon states. In the IPNDV model, verification is conducted by a multilateral body composed of inspectors from all parties to a disarmament agreement, including both states with and without nuclear weapons.

The HEU Transparency Agreement established a precedent between NWS for balancing effective verification with the protection of sensitive information. Sensitive information such as the mass of individual containers, the number and type of warheads, and the presence of minor uranium isotopes (e.g., ^{234}U, ^{236}U) was not shared. Only aggregate data (total HEU mass, blend stock, and product) was disclosed, and verification was designed to avoid revealing classified details. Key practices included:

- **Selective sharing of technical data:** Only aggregate masses and enrichment levels were shared, while the specifics of warhead components and minor isotopic composition were withheld.

- **Verification technologies:** The use of the "enrichment meter" technique allowed inspectors to confirm ^{235}U enrichment of materials in containers without revealing other isotopic or compositional details. A system was developed and installed at the three Russian downblending facilities. The system continually monitored the enrichment and flow of the UF_6 in the HEU, blendstock, and product pipes of the blending systems.

- **Diversified responsibilities:** The establishment of a Transparency Review Committee was authorized to resolve technical issues with the implementation of the monitoring agreement at the various facilities. Also, the agreement named "Executive Agents" for each side (USEC, TENEX) that would handle all the commercial aspects of the agreement. This allowed the Transparency Program to focus on the nonproliferation objectives of the agreement.

Beyond the U.S.-Russian HEU Purchase Agreement, future HEU disposition monitoring could use other downblending methods that would lead to differences in the monitoring and verification approach. For example, the U.S. Department of Energy (DOE) has implemented different pathways for HEU downblending, notably at the Savannah River Site (SRS) H-Canyon facility. As detailed in the Savannah River National Laboratory report, since 2003, SRS has processed off-specification HEU (containing fission products or isotopic impurities) from across the DOE complex, converting it into LEU for use in Tennessee Valley Authority (TVA) reactors.[7] Notably, this process involves converting to HEU nitrate solution, purification, and downblending using natural uranium nitrate solutions to achieve the desired enrichment and impurity profile. The

[7] V. E. Magoulas, *Savannah River Site's H-Canyon Facility: Recovery and Down Blend Uranium for Beneficial Use* (SRNL-MS-2013-00081), Savannah River National Laboratory, presented at INMM 54th Annual Meeting, July 15–18, 2013, Palm Desert, CA, USA.

resulting product is then transferred for eventual conversion to LEU fuel. This pathway demonstrates a different pathway for HEU disposition strategies, accommodating material not suitable for direct commercial fuel use and providing economic and nonproliferation benefits. The SRS approach also highlights the potential variation of infrastructure and processes included in a future monitoring regime.

The historical experience of the HEU Transparency Agreement and ongoing domestic downblending initiatives provide a strong foundation for the verification and management of HEU disposition under the IPNDV framework. Both precedents underscore the need for rigorous monitoring, careful handling of sensitive information, and adaptable technical procedures to ensure that weapons usable HEU is verifiably converted.

Potential Processes, Procedures, Techniques, and Technologies (PPTT)

As discussed above, the fissile material output from Step 14 in the approach examined here has likely lost many of its sensitive characteristics and might hence be available for detailed verification. Because these procedures likely will be similar to the established International Atomic Energy Agency (IAEA) safeguards approach, we will not discuss these downstream verification options further.

When it comes to verification technologies for the activities in Step 14, in analogy with Step 8 as described above, the technology options will primarily rely on perimeter monitoring and chain of custody measures, and inspection-based verification because of the proliferation concerns mentioned earlier. However, the complexity of the changing material form, the transition from item-to-bulk, and the possible presence of other nuclear material (e.g., downblend materials and waste streams) may lead to differences in the verification approach in Step 14.

During an inspection of the dedicated disposition processing and storage areas, it may be necessary to seal potential diversion pathways. Depending on the specifics, this could be by either adhesive seals and/or loop seals. Another chain of custody technology that could be applicable is change detection, to verify that the dedicated processing area remains as designed and agreed.

The IPNDV dismantlement approach assumes that the nuclear warhead SNM will be under chain of custody when it is transferred from Step 13. For redundancy, radiation signatures of the items coming from Step 13 could also be checked if necessary, for example if the chain of custody has been broken. If inspectors are not present when a declared container with SNM enters Step 14, radio-frequency identification (RFID) readers with the ability to record seal integrity could verify that the container has entered.

Finally, it should be noted that at this stage individual items are being verified. During processing, there may be nuclear material used as blend stock to appropriately transition the fissile material into its desired final state (e.g., material suitable for fuel). Although the unknown properties of the blending stock may obscure certain proliferation-sensitive properties of the original warhead material, such as mass and isotopic composition, declaring and verifying the details of the Step

14 blend material could indirectly reveal proliferation-sensitive properties. At the same time, specifying requirements for the downblended input and output streams (e.g., input is below mass and/or enrichment threshold of plutonium or uranium isotopes and output is above) could provide additional confidence about the input fissile material while protecting proliferation-sensitive properties. Striking the right balance that considers both end-use requirements and sensitive information protection will be important in developing verification mechanisms for disposition.

Given that the SNM is already under chain of custody and that a blending stock of unknown composition will have to enter the dedicated disposition areas in this scenario, the perimeter monitoring cannot be used to control all the input to the downblending process. Together with the fact that the downblending process itself will occur without any monitoring, it is important that the perimeter monitoring correctly verify all the outgoing flow from the process area (given that other potential diversion pathways are addressed by sealing). A secure portal could be maintained by including occupancy and directionality sensors (which may also verify minimum object speed, weight, or size if agreed upon); for example, two break beams that can verify direction and speed of object, as well as to trigger the radiation portal monitor and, potentially, a CCTV system. In order to be effective, the CCTV system should cover areas where the allowed exit points are situated, without revealing other nearby activities beyond the verification scope.

Portal monitors could include both gamma and neutron detection, although the limitations of detecting shielded HEU should be taken into consideration in the overall system design; for example, weight sensors could be added to the portal, and reasonable weight limitations could be agreed to prevent the risk of shielded HEU diversion. Additionally, the design and implementation of the portal should minimize the possible standoff, and limit and verify the objects speed as they are moved by the portal to ensure reasonable probability of detection. Additionally, design elements to minimize nearby background sources via portal monitor location choice and collimation is also important for optimizing performance.

Portal monitors are primarily used for absence verification, but a more advanced portal monitor capable of verifying a nuclear material attribute may be capable of presence measurements. Any items that cannot be resolved via the portal technology selected should be stored until they can be cleared during an onsite inspection. This could be verified, if inspectors have remote access to the portal monitor data; alternatively, inspectors could check saved alarm data during onsite inspections if inspections occur frequently enough, and if the system could store alarm data in a robust, tamper resistant manner. For example, radioactive waste or downblended material would likely not be distinguishable from treaty accountable SNM using simple radiation threshold portals, but an inspector could perform absence measurements on these items with other verification tools (e.g., high-resolution spectral measurement or neutron multiplicity measurement). In general, it will be important to have a low false alarm rate, in particular if inspectors are not present at the site at all times. For absence, the alarm threshold must be high enough so that nearby operational activities do not trigger an alarm. If the same portal monitor is to be used for presence, there should be an attribute with sufficient differences identified that can positively identify treaty accountable SNM without opening a potential diversion pathway for such material. If this is found to be too complex, bulk downblended materials and waste containers may need to be stored until they can be cleared during an onsite inspection.

In Step 14, the only input that portal monitors could verify are the SNM containers entering (via RFID tag and seal readers). However, if no inspectors are constantly present, the portal monitors may primarily be used to verify that no nuclear material has left between inspections; interim inspections would be needed to allow hosts to remove nuclear material from the monitored area with verification measures to positively confirm containers leaving are consistent with agreed upon specifications, and that no additional treaty accountable SNM is leaving.

The extent of inspector presence also has direct impact on the monitoring equipment data management. If inspectors have a continuous presence, or at least visit the relevant facilities often, it may suffice to have all the verification data stored locally. The inspectors would then have to download the data onsite, and to increase confidence that data have not been tampered with, the host and inspector could agree on a method to secure the data (e.g., by private-public keys or hashing). However, if extended time intervals exist between inspectors onsite, retrieving data locally may not provide a timely verification. Under such circumstances, transferring the data remotely using methods that protect the sensitive information is an option that should be considered.

Aligning specific PPTT with the existing facility-level and state-level nuclear material control and accounting practices in individual treaty parties may have key advantages. For example, existing Material Balance Areas may define where physical inventories of nuclear materials are confirmed as part of normal facility operations with Key Measurement Points identified (input and output locations to an Mass Balance Area where measurements are taken to update material flow or inventory); these definitions and associated technical verification may provide useful portal and perimeter locations, measurement techniques, and inspection timeframes to incorporate into treaty verification implementation. For Step 14 in particular, these processes may already have methods of confirming and tracking "item" and "batch" material accountancy.[8] Discussions of particularly comprehensive implementations of nuclear material control and accounting procedures and technologies used can be found in Siegel et al.[9] and more recent technical development can be found in research communities, such as the International Nuclear Material Management (INMM)[10] organization and the European Safeguards Research and Development Association (ESARDA).[11]

In this summary of potential PPTT options, we have assumed that verification technical approaches may need to account for proliferation-sensitive information, which will likely be reduced from the beginning to the end of this step. However, proliferation-sensitive information may also need to be protected over time as items transition into a mass flow—the Step 13 input

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[8] *Nuclear Material Accounting Handbook*, International Atomic Energy Agency IAEA-SVS-15, Vienna, 2008, https://www.iaea.org/publications/7828/nuclear-material-accounting-handbook.

[9] J. Seigel, J. Steinbruner, and N. Gallagher, *Comprehensive Nuclear Material Accounting: A Proposal to Reduce Global Nuclear Risk*, Center for International and Security Studies at Maryland, March, 2014.

[10] Institute of Nuclear Materials Management, https://inmm.org/.

[11] European Safeguards Research & Development Association, https://esarda.jrc.ec.europa.eu/.

stream is directly tied to a specific number of warheads and potentially the history of declarations and verifications about those items. Sensitive information must not be revealed over time by measuring the details of the bulk material exiting Step 14. In the HEU Purchase Agreement between the United States and Russia, the downblending was monitored by measuring the isotopic enrichment and mass flow as the weapons-grade material was blended down to LEU.[12] Although past disposition agreements such as the HEU Purchase Agreement implemented relevant verification technologies, such as the process monitoring flow meters and gamma ray detectors, key differences are noted between these past agreements and Step 14 (e.g., no link exists between the mass of HEU components and the number of nuclear weapons and the agreement was between two NWS).

Conclusion

In this report, a general verification concept for the disposition of the SNM components from nuclear warheads has been presented. Its primary focus has been on perimeter monitoring and absence measurements of fissile material. As a next step, it would be desirable to test the practicality of this concept for both plutonium and HEU through realistic exercises. This report also discusses suitable, proven monitoring procedures for closing any gaps that may be identified by these exercises.

Depending on the end point of the disposition process (declassification with subsequent safeguards, mixing with high-level radioactive waste or military non-weapons use), further refinements could be made.

[12] See for example Lawrence Livermore National Laboratory, S&TR April/May 2013, 16–19.

About IPNDV the International Partnership for Nuclear Disarmament Verification

The International Partnership for Nuclear Disarmament Verification (IPNDV) convenes countries with and without nuclear weapons to identify challenges associated with nuclear disarmament verification and develop potential procedures and technologies to address those challenges. The IPNDV was founded in 2014 by the U.S. Department of State and the Nuclear Threat Initiative. Learn more at www.ipndv.org.