Nuclear Disarmament Verification and Technology Options for Absence Measurements

December 2025

Introduction

Verification is an integral part of any nuclear disarmament treaty as it provides data to determine whether or not parties to an agreement are abiding by their obligations. The process of verification, including notifications and on-site inspections, provides information about the activities governed by that agreement. Historically, nuclear arms control has primarily focused on reductions and limitations of the total number of delivery vehicles for nuclear weapons, and not the total number of nuclear warheads. For future treaties regarding reductions and/or limitations of nuclear warheads, verification will grow in importance. In a broad sense, this will be somewhat reminiscent of how the International Atomic Energy Agency performs safeguards that both verify the correctness and completeness of a non-nuclear weapons state's peaceful nuclear program. However, due to the safety and security issues involved with nuclear weapons as well as non-proliferation obligations specifically associated with nuclear weapons, it will be more challenging to implement verification measures.

In some inspections, the primary goal of the inspecting entity is to verify that no more nuclear warheads are present in a state beyond the number of warheads allowed under an agreement. In these circumstances, the inspecting entity will verify the absence of nuclear warheads by using inspection processes, procedures, techniques, and technologies (PPTT) to examine items declared to not be nuclear warheads. An absence-based approach may avoid or reduce certain safety and security concerns that the inspected party may have.

Effective nuclear disarmament verification is composed of four different but interrelated elements: processes, procedures, techniques, and technologies, which act in tandem to provide effective verification of compliance. This report focuses on the "technologies" element when verifying the absence of nuclear warheads. It describes different technologies that could be used to confirm the absence of nuclear warheads and highlights the advantages and disadvantages of each.

Given that many of the technologies addressed are regularly used outside of the nuclear arms control context, they are not necessarily adapted for the safety and security aspects involved with verifying nuclear warheads and related activities without some degree of modification. This is an issue even for absence measurements, where, for example, an absence measurement is performed on an item that contains sensitive information (e.g., verifying a nuclear weapon component is *not* a nuclear weapon) or is in the vicinity of other nuclear warheads/components. Such a situation may necessitate using an information barrier (IB). In addition to such cases, there is also a need to be able to authenticate and certify inspection equipment to establish confidence in the correct functionality of the equipment from both host and inspector perspectives.

The type of technologies that may be implemented for absence measurements in a nuclear arms control verification system also depends on the classes of objects that are treaty accountable. Throughout its work, the IPNDV has defined nuclear warheads as objects containing both special nuclear material (SNM) and high explosives (HE). Therefore, the complete warheads, as well as the separated SNM and HE components, are considered to be treaty accountable items (TAI). This report, therefore, considers technologies that are applicable to verifying absence of nuclear warheads, SNM, and/or HE components; the utility of each is scenario dependent.

Technology Considerations

The types of technologies that are applicable for verifying absence of nuclear warheads, SNM, and/or HE components are essentially identical to the ones used for verifying presence. However, the requirements of the equipment and the way the equipment is used may differ considerably, and lead to significantly different design choices. As an example, to verify the presence of a nuclear warhead, inspectors may need to use a rather detailed energy spectrum of the emitted gamma-rays to have confidence that the object is consistent with the treaty definition of a nuclear warhead (disregarding the complexity due to the need for an IB in this case). On the contrary, to verify the absence of a nuclear warhead, a total gamma-ray flux for all energies below a certain threshold may suffice.

In certain circumstances, verifying the absence of radiation will not meet the "absence verification" goal with a sufficient degree of confidence; for example, if it is necessary to verify the absence of a nuclear warhead when another type of SNM item is present (e.g., nuclear components). Conversely, requiring more varied and/or detailed information will in general add to the number of necessary pieces of equipment and/or to an increased burden on equipment authentication and certification. Again, to what extent this will be necessary depends on specific scenarios.

An additional aspect is the potential need for verifying the absence of HE. Even in a scenario where HE is not treaty accountable, absence measurements of HE could still be valuable. For example, verifying that a nuclear warhead has been dismantled is contingent on separating SNM and HE. Because the dismantlement process cannot be monitored directly, the dismantlement can be confirmed post-dismantlement by verifying that no items presented for inspection contain co-located SNM and HE. Therefore, verifying that any item containing SNM after dismantlement also is absent of HE confirms the absence of a nuclear warhead. In this way, absence measurements of HE could be a valuable procedure to confirm nuclear warhead dismantlement.

Finally, the "absence" of a nuclear warhead, SNM, or HE may require that a declared attribute "threshold" quantity is defined. For example, a nuclear weapon could be defined as having above a quantity of SNM above a given threshold.[1] This defined and agreed upon threshold provides a metric that a relevant absence verification technology can be specifically designed to detect. It is important to define the threshold to be lower than nuclear weapons-relevant-quantities (i.e., doesn't allow for diversion pathways); however, if the threshold is too low, the technology options for detecting very small quantities will likely be more limited, more complex, or less reliable. Additionally, the threshold can serve to exclude certain items from further inspection, such as containers below a specific size. However, if the threshold is set too low, it could significantly increase the number of items requiring inspection, thereby creating an unnecessary, and unmanageable burden.

Designing equipment to detect small quantities of materials often requires sensitivity to weak signatures. However, the effectiveness of detection can be compromised by changes in measurement conditions, such as the changing surroundings and background signatures.

Technology Options

Table 1 summarizes the technology classes considered for absence measurements of nuclear warheads, SNM, and HE. In all cases, we have assumed that the absence measurement does not detect any radiation or other information from nearby objects that are not specified to undergo the absence measurement. As discussed above, if that is not the case, an IB may be needed. All times listed in the table for setting up and using the technology are rough estimates.

The technologies can typically be used for absence measurements during all 14 steps of the IPNDV dismantlement life cycle (Figure 1), although that does not imply that they are all an optimal—or even good—choice at all steps. To implement the most optimal choices of technologies, one has to evaluate several advantages and disadvantages, among them the time available for setting up the equipment and collecting data, the mobility of the equipment, whether the absence measurement is confined to a limited area or would be used over a wider area and if multiple nuclear warheads are nearby.

The various steps also have inherently different limitations: for the transport steps, the absence measurement, if provided for by an agreement, would generally have to be performed at the exit and entry points of the relevant facilities, and not during the actual transportation. At step 14, where SNM is converted to a form and composition that is not directly useable in a nuclear warhead (if applicable), measuring absence of SNM within the facilities would be challenging due

[1] J. Yan and A. Glaser, "Nuclear Warhead Verification: A Review of Attribute and Template Systems," *Science & Global Security* 23, No. 3 (2015): 157–170, https://doi.org/10.1080/08929882.2015.1087221.

to the nature of the processes; for transportation, it may involve controlling the entry and exit points for these facilities.

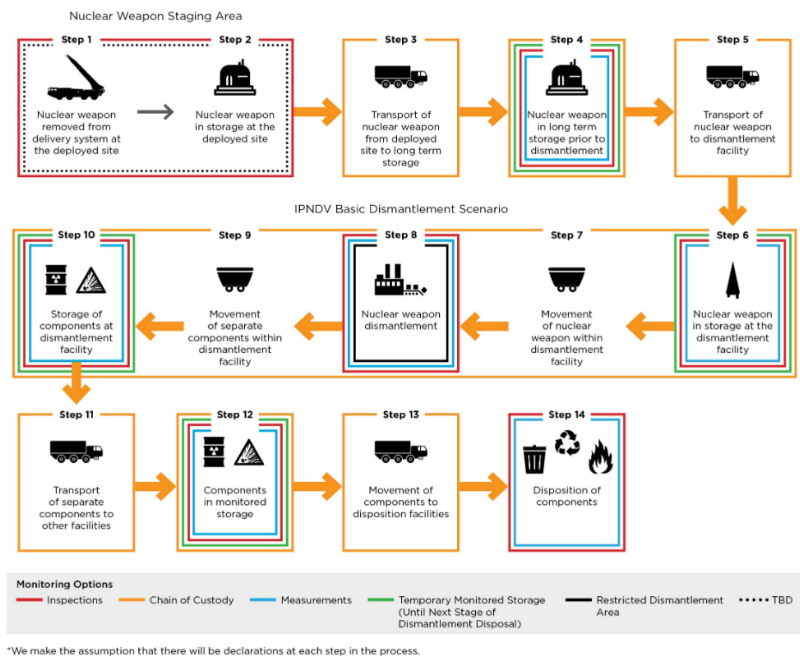

Figure 1: The IPNDV 14 Steps for Dismantlement

For completeness, we also give a short description of the detection principle for each technology class, remembering that absence measurements should not detect the presence of nuclear material (for a more thorough discussion on each technology and different detection methods, we refer to the IPNDV dismantlement interactive at www.ipndv.org).

Passive Methods

- **Passive Gamma Detection:** Detects emitting gamma radiation from an object, could be total count rate or spectroscopic information; the latter could give nuclide and isotopic information of the emitting object. In the presence of neutron emitting SNM, it could indicate absence of HE from spectroscopy and absence of (n, γ) capture reactions.
- **Passive Gamma Imaging:** Detects emitting gamma radiation and absence of HE as above, and in addition can provide location and shape of the emitting object (although somewhat vulnerable to self-attenuation of the object).
- **Passive Neutron Counting:** Can detect neutron emissions from an object, including coincidence and/or multiplicity neutron emissions from objects that undergo spontaneous

fission as well as the direction of the emission. With some energy resolution, presence or absence of moderated (low energy) neutrons would indicate presence or absence of HE.[2]

- **Passive Neutron Imaging:** Can make an image of the neutron emitter; provides a not very detailed shape and location of a distributed source. Could possibly indicate presence or absence of HE.
- **Muon Tomography[3]:** Detects scattering/deflection of naturally occurring muons and creates a non-detailed image. Muons scatter mainly against heavy elements, but cannot distinguish between them (e.g., plutonium, uranium, or tungsten). The method cannot be used to verify absence of HE.

Active Methods

- **Gamma/Neutron Transmission:** A gamma/neutron source is used to estimate the amount of shielding as well as moderation (indicating HE) in an object of interest. Would indicate absence of heavy and/or light elements but not specific materials, elements, or isotopes, although dual energy transmission techniques can provide limited indication of elemental composition.
- **Active Multiplicity Counting:** A neutron source is used to induce fission chains in the presence of SNM and gives a quantity of SNM. In this paper, the method also encompasses detection approaches such as measuring delayed neutrons and differential die away. Does not typically measure moderated neutrons, so limited use for absence measurement of HE.
- **Active Fast Neutron Imaging:** Neutrons can be used to image interior contents of a container, typically with a lower resolution than x-rays. To detect SNM, it needs to detect fission-neutron emission; for HE, it needs to account for moderated neutrons.
- **High-Energy X-Ray Imaging:** Can be used to image interior contents of a container and is sensitive to changes in material density. Could provide 3D volumetric information, shape, location, effective atomic number, density, mass, material type. The technology can identify objects that are surrounded (hidden) by other objects. Could detect (the absence of) both HE and SNM.
- **Nuclear Resonance Fluorescence:** Irradiates a material with high-energy photons and then detects the photons that are subsequently emitted by the material. The gamma-ray spectrum gives isotopic information for SNM and ratios between carbon and nitrogen as well as carbon and oxygen for HE determination.
- **Raman High Explosives Identification:** An active spectroscopic technique to observe vibrational, rotational, and other low-frequency response modes of a molecular system;

---

[2] Although this signature is consistent with HE being present, other common materials such as plastic would also produce low-energy neutrons. In addition, strong neutron absorbers such as cadmium or gadolinium easily shield thermal neutrons.

[3] IPNDV Working Group 3: Technical Challenges and Solutions Nuclear Material (8)—Technology Data Sheet, August 25, 2016, http://ipndv.org/wp-content/uploads/2017/11/WG3-NM8-Muon-Tomography-Technology-Data-Sheet-Final.pdf.

when compared to known spectra, can be used to confirm presence and identification of HE. The method does not detect SNM.

- **NQR-Explosive Identification System:** Active spectroscopic technique where select nuclei are excited using radio waves and the response is observed; when compared to known spectra, it can be used to confirm presence and identification of HE. The technology does not detect SNM.
- **Fast/Thermal Neutron Interrogation System:** In this paper, this means measuring gamma emissions in response to excitation by neutron bombardment. The resulting spectra can be used to confirm presence and identification of HE. It can also be used to image other materials and could therefore measure absence of SNM.
- **Compton Backscattering Cameras:** Active x-ray technique that uses x-rays that are backscattered from crystal structures of the relevant material. The method can detect and identify different HE but does not detect SNM.

Table 1: Technology Options for Verifying Absence of a Nuclear Weapon, SNM, and HE

Technology Class	Time for Activity (minutes, hours)		Verification Value	Comments
Passive Gamma Detection	**Set-up:** **Measurement time:**	Up to 1h Up to 1h	**High** for absence of plutonium, **low** for uranium. **Medium** for absence of HE if plutonium is present.	• Vulnerable to external shielding. U-235 signals vulnerable to even small amounts of shielding. • A handheld detector is preferred for a container, but time consuming for wider area. • Detector choice would differ if verifying absence of specific SNM vs. absence of **any** gamma radiation (prioritizing detection efficiency versus energy resolution).
Passive Gamma-Ray Imaging	**Set-up:** **Measurement time:**	Up to 1h Up to 2h	**High** for plutonium absence, **low** for uranium. **Medium** for absence of HE if plutonium is present.	• Vulnerable to external shielding. Small amounts of shielding will block potential signals of U-235. • Provides location and shape, if an object is detected. • Imaging needs longer data collection time, more practical for static situations.
Passive Neutron Counting	**Set-up:** **Measurement time:**	Up to 30m Up to1h	**High** for plutonium absence, **low**	• Could be either total rate emitted, multiplicity, or directional.

Technology Class	Time for Activity (minutes, hours)		Verification Value	Comments
			to **medium** for uranium. **Medium** for absence of HE if plutonium is present.	• Low spontaneous fission rate in uranium makes absence more challenging.
Passive Neutron Imaging	**Set-up:** **Measurement time:**	Up to 10m Up to 4h	**High** for plutonium absence, **low** for uranium. **Medium** for absence of HE if plutonium is present.	• Low fission rate in uranium makes this method practical only for plutonium. • Because of long collection time, best for static situations.
Muon Tomography	**Set-up:** **Measurement time:**	Hours to days	**High** for absence and presence of heavy elements. **Low** for absence of HE.	• Does not distinguish between different heavy elements. • Because of long collection time, best for static situations. • Due to large footprint, may require modification to facility. Portable muon imaging system exists and can be deployed to the facility if very long measurement times are acceptable.
Active Gamma/ Neutron Transmission	**Set-up:** **Measurement time:**	Up to 1h Up to 30m	**High** for shielding or moderation in general. **Low** for SNM or HE specifically.	• Measures only general aspects of transmission. • High confidence of SNM or HE absence if object does not contain heavy or low-Z material, but still indicates shielding or moderation.
Active Multiplicity Counting	**Set-up:** **Measurement time:**	Up to 1h Up to 1h	**High** for both plutonium and uranium, **low** for HE.	• Could also measure delayed and differential die-away neutrons.
Active Fast Neutron Imaging	**Set-up:**	Up to 1h Up to 1h	**High** for SNM,	• Needs to measure moderated neutrons for high confidence in HE absence.

Technology Class	Time for Activity (minutes, hours)		Verification Value	Comments
	Measurement time:		**medium** to **low** for HE.	
X-Ray Imaging	**Set-up:** **Measurement time:**	Up to 1h Up to 1h	**High** for general absence of heavy or low-Z material. **Low** for SNM or HE specifically.	• Measures only general aspects of transmission. • Easily shielded with dense materials, likely cannot see through high-Z materials.
Nuclear Resonance Fluorescence	**Set-up:** **Measurement time:**	Up to 30m Several hours	**High** for SNM and HE.	• Hydrogen is the only element that cannot be detected.
Raman High Explosives Identification	**Set-up:** **Measurement time:**	Up to 30m Up to 30m	**High** for HE, **low** for SNM.	• A technology that only detects HE, not SNM. • Dependent on HE stored in a semi-transparent container; would not likely work with a sturdy wooden container for example.
NQR-Explosive Identification System	**Set-up:** **Measurement time:**	1h 1h	**High** for HE, **low** for SNM.	• A technology that only detects HE, not SNM. • Only bulk quantities can be detected. • Likely works with a variety of enclosures but not metal ones.
Fast/Thermal Neutron Interrogation System	**Set-up:** **Measurement time:**	10m 10m	**High** for HE, **medium** to **low** for SNM.	• Needs compositional information ahead of time; container composition dependent.
Compton Backscattering Cameras	**Set-up:** **Measurement time:**	10m 1m	**High** for HE, **low** for SNM.	• Vulnerable to shielding by dense materials.
X-Ray Computed Tomography	**Set-up:** **Measurement time:**	10m 1m	**High** for HE, **high** for SNM.	• Will not penetrate through thick materials with a high density.

Conclusion

The level of confidence these technologies can provide depends not only on the intrinsic capabilities of the technologies, but also on the context: when they are used, where they are used, and the use of other potential measures that complement them. Such other measures include but are not limited to chain of custody techniques (unique identifiers, tags and tamper-indicating seals or other tamper-indicating devices) and the frequency and duration of inspections.

The technologies discussed can also be implemented in different ways. As a specific example, for passive gamma detection, one could use a handheld device for absence measurements on specific objects, whereas a portal monitor at the entry and exit points of a facility would be more suitable for perimeter monitoring.

As noted earlier, the listed technologies are also relevant for presence measurements, although safety and security considerations would generally be of more concern for presence confirmation. Although categories of technologies are relevant for both absence and presence verification, the technical requirements are likely to require different equipment designs. In other words, a technology designed for performing absence measurements is unlikely to be optimally designed for presence measurements.

Finally, these technologies have been evaluated in the context of the IPNDV 14 step model. Significant differences in employment strategies could surface if their use were expanded to other areas of the nuclear weapons lifecycle. Such a study could highlight how different technologies have different values in a reduction versus a limitation scenario and find other potentially useful technologies that were not included in this study.

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.