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The Absent-Minded Inspector

Confirming the Absence of Nuclear Warheads via Passive Gamma-Ray Measurements

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Abstract. Arms-control agreements between the United States and Russia negotiated after the end of the Cold War have imposed limits on the number of deployed strategic nuclear weapons. Verification of these agreements has relied on onsite inspections, sometimes supported by radiation detection techniques to confirm that an object is non-nuclear. Such absence-confirmation measurements, so far, rely on the detection of neutron emissions associated with the presence of plutonium, but they would be inadequate for uranium devices. Alternative instruments relying on the detection of gamma emissions could simultaneously confirm the presence or absence of both plutonium-based and uranium-based weapons, complementing existing systems that detect neutrons, which can only confirm the absence of plutonium devices. Here, we demonstrate an inspection system and prototype device that uses only passive gamma radiation detection techniques to confirm the absence of gamma emissions from containerized objects. Such a system would be particularly valuable for next-generation arms-control agreements that limit total numbers of weapons, including those deployed, in storage, and slated for dismantlement. We have conducted extensive Monte Carlo simulations to support the development of a verification protocol and detection algorithm, and exemplify the viability of the proposed system using standard laboratory check sources and MCNP simulations for simplified configurations of special nuclear material.

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Background

For thirty years, international research and development efforts have sought to develop inspection systems that can confirm the authenticity of a nuclear weapon to support the verification of a future treaty that requires verified warhead dismantlement. With few exceptions, only limited progress has been made toward certifying and authenticating such candidate systems because of security concerns associated with such inspections.[1] Warhead dismantlements, however, may not have to be verified anytime soon.[2] In fact, next-generation nuclear arms-control agreements, either bilateral or multilateral, could place limits on all weapons in the stockpiles, including those that are non-deployed and in storage.

The most basic approach to confirming numerical limits as part of an all-warhead agreement could be to rely solely on baseline declarations, followed by regular data exchange. This is essentially the approach followed by New START for deployed strategic nuclear weapons, but it can in principle be expanded to non-deployed weapons. In this case, during an onsite inspection of a site selected by the inspector, which can either be a site that is declared to hold treaty-accountable items or not, the host gets "credit" for the number of items declared for that site and identifies those items as such. These declared items will be accepted as treaty-accountable items and never accessed or inspected.[3] The inspectors would then be allowed to confirm that other items available at the site are in fact not treaty accountable. During the negotiations of the underlying agreement, the parties could agree on certain physical characteristics of objects that qualify for further inspection, such as the minimum dimensions of a storage container. In many cases, the host may be able to simply provide visual access to items or containers that have been flagged by the inspector to demonstrate that the item is not treaty accountable; there may be cases, however, where this approach is not possible or practical. In these cases, the inspector could be allowed to take radiation measurements to confirm the "absence of a nuclear weapon" or, more specifically, to confirm that a container does not contain sufficient amounts of plutonium or uranium to make a nuclear weapon. In principle, this can be done with simple neutron or gamma (gross) count measurements.

Simple neutron detectors have been used for many years as part of New START to confirm that an object is "non-nuclear."[4] Only plutonium, however, emits neutrons in significant quantities; uranium does not, and the technique can therefore not be used for uranium-only weapons or weapon components. Relying on the detection of gamma emissions, as a complement to neutron measurements, could simultaneously confirm the absence of both plutonium-based and uranium-based weapons, which may be relevant for other types of nuclear weapons or weapon components. Gamma radiation is more easily shielded than neutron radiation, however, which may require additional provisions in the inspection protocol. While such gamma-based tools have not been used for arms-control verification purposes to date, the technology itself is straightforward and easily deployable.

Absence measurements have several fundamental advantages as they can be non-intrusive by design. In a verification regime based on absence measurements, no weapons should ever be part of an inspection, and safety and security concerns would therefore be dramatically reduced. Information barriers, if needed at all, could be relatively simple.[5]

Analytical Basis for Absence Detection

Plutonium and highly enriched uranium are the key ingredients in nuclear weapons. While the exact amounts and configuration of these materials in weapons are classified, it is known that nuclear weapons contain kilogram quantities of plutonium or uranium, or both. In this work, we assume at least one kilogram of weapon-grade plutonium (WPu) containing 0.93 kg of Pu-239 or the presence of four kilograms of highly enriched uranium (HEU) containing 0.28 kg of U-238. The 4:1 ratio we use here is based on the relative values of uranium-reflected critical masses of HEU and plutonium. Of course, other values could be agreed upon by the parties considering deployment of such a verification approach.

We focus on passive radiation detection of gamma rays and employ low-resolution gamma spectroscopy with regions of interest around selected gamma energies corresponding to prominent plutonium and uranium lines. Constraining the measurement to defined regions of interest minimizes background effects and increases the specificity of the measurement. For uranium, we consider the decay chain of U-238 to determine the relative concentrations of Th-234, Pa-234, and U-234 based on their half-lives and assuming the isotopes are in secular equilibrium.[6] For plutonium, we use a reference composition (DOE 3013) with a Pu-239 content of about 93.5% and no Am-241.[7] The energy windows, gamma intensities, and net emission rates for spherical shells of nuclear material are tabulated in Table 1.

Following the notation used in Fetter et al., the detected signal, in counts per second, for a given radiation source is given by $S_C = (I \times M)\,(G \times F)\left(\frac{A_D}{4\pi R^2}\right)\epsilon$.[8] Here we use S_C to indicate the net signal from a containerized item. The first term represents the absolute emission rate, where I is the intensity of radiation in the particular region of interest (in gammas per second per kilogram of the respective isotope) and M is the mass of the same isotope. The second term accounts for self-shielding (G) and external shielding (F) of the configuration. The third term is the detectable fraction determined by the solid angle covered by the detector. The final factor (ϵ) is the energy- and material-dependent

Table 1: Gamma emissions from assumed minimum quantities of special nuclear material. Self-shielding factors (escape probabilities) have been determined with MCNP calculations for spherical shells with an outer diameter of 10 cm. While the actual geometries and configurations are classified, the United States has declassified the fact that "thin spherical shells of fissile materials [are used] in weapons,"[9] and in 2020, the U.S. Department of Energy noted that pits are "spherical shells of plutonium about the size of a bowling ball."[10] Emission-rate data for the regions of interest are from www.nndc.bnl.gov/nudat2.

Property	**Pu-239**	**U-238**
Mass	0.93 kg	0.28 kg
Region of interest	300–500 keV	950–1050 keV
Dominant gamma line	(multiple)	1001.0 keV
Emission rate of point source	1.30×10^{8} s^{-1}	2.92×10^{4} s^{-1}
Shell outer diameter	10 cm	10 cm
Thickness of shell	0.17 cm	0.78 cm
Escape probability	24.8%	25.5%
Effective emission rate of shell	3.23×10^{7} s^{-1}	7.43×10^{3} s^{-1}

detector efficiency. We make two important assumptions regarding shielding. First, the containerized item is assumed to be axially symmetric about its central vertical axis because a dishonest host would want to shield the inspected item equally well in all directions. Second, all observed attenuation, including that due to self-shielding of the nuclear material, is attributed to an equivalent thickness of "external" lead shielding.

We must also set a threshold for distinguishing a signal above the prevailing background. Currie's equation, $S_C\, T_M = z^2 + 2\, z \sqrt{2\, (S_B\, T_M)}$, provides the minimum detectable signal for the detection of nuclear material, where we use $z = 2.3262$ for a detection probability of 99% and a false-alarm rate of 1%. S_C is the net signal from the inspected container from above, S_B is the background signal in the absence of the container, and T_M is the measurement time for the inspected item and the background. In practice, this formalism can be utilized with experimental values from the field to confirm the absence of a predetermined threshold quantity of nuclear material.

To evaluate the practical limits of an absence-confirmation system, we assume a shielded and collimated, two-inch diameter sodium-iodide (NaI) detector operating in a relatively low-background environment. The resulting minimum detectable quantity of weapon-grade plutonium (93% Pu-239) and highly enriched uranium (7% U-238) is shown in Figure 1 for a standoff distance of 70 cm and for a range of measurement times and lead-equivalent effective shielding.[11] Although we ideally seek to confirm the absence of a warhead, the maximum external shielding is calculated such that a warhead would be detectable, if present.

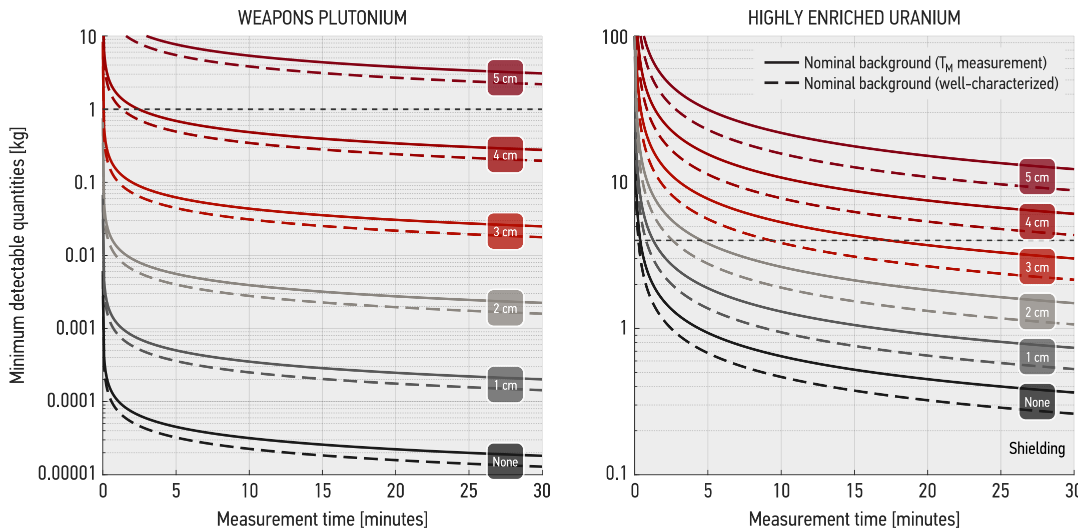

Figure 1: Minimum detectable quantity of plutonium and uranium versus measurement time. Each curve corresponds to a different effective shielding thickness with a fixed standoff distance of 70 cm and a nominal background measured in our laboratory (2.95 cps in 300–500 keV and 0.39 cps in 950–1050 keV). Data are for a detection probability of 99% and a false alarm rate of 1%. Solid lines are for a background measurement that is as long as the measurement itself; dashed lines indicate a well-characterized background with negligible uncertainty. Proposed threshold masses for WPu (1 kg) and HEU (4 kg) are indicated.

Verification Protocol

To apply the theory supporting absence detection, we propose a five-step measurement campaign (Figure 2), including: background acquisition; detector calibration; characterization of a reference source; shielding estimate of the inspected container using the reference source; and inspection of the container itself. We envision that the host and inspector will agree on a measurement time for each of these steps; in theory, the host can propose a measurement time that would be sufficient for an unambiguous outcome.

The verification protocol begins with standard background acquisition and detector calibration. Ideally, the inspection should be conducted in a low-background environment in order to minimize measurement times. It would also be in the interest of the host to provide such an isolated environment to not only expedite inspections, but to also avoid inconclusive outcomes. The background is acquired before calibrating the detector so that the presence of an acceptable calibration source can be confirmed.

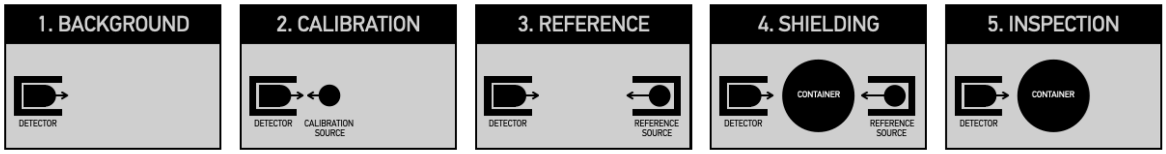

Figure 2: Steps of the proposed verification protocol for absence measurements. The measurement campaign begins with acquiring the background and calibrating the detector. A reference source is then used, with and without the inspected object, to determine the shielding estimate. The final step is to measure only the inspected object.

A reference source is then placed on the "far side" of where the inspected container will be placed later in the protocol. This reference source is used to estimate the shielding present in the inspected container. In order to make this estimate, the strength of the source must first be measured. We use the 661.7 keV line of cesium-137. Similar to the calibration source, the presence of an adequately strong calibration source is verified by comparing the count rates in those channels where the cesium peak is expected against the previously measured background. If the source is deemed sufficiently strong, the container to be inspected is moved into position between the detector and the reference source. The reduction of the signal compared to the previous measurement is used to estimate the total lead-equivalent effective shielding.

The final step is to remove the reference source and then measure the gamma-rays emitted from the container itself.[12] At this stage, the effective shielding thickness is calculated based on the spectra acquired in the last three steps. Using the background spectrum and the counts of a notional bare source, the maximum shielding thickness is also calculated. The final inspection result is then deduced by simple comparison with these threshold values in each region of interest. If the inspection spectrum exceeds the critical level corresponding to Currie's equation, $L_C = z\sqrt{2\,(S_B\,T_M)}$, then an anomaly is detected; however, detecting an anomaly does not guarantee the presence of the threshold quantity. If the inspected spectrum is below the critical level and the estimated shielding thickness exceeds the calculated maximum shielding, then the result is inconclusive; this may be due to a combination of high background levels, excessive shielding, and insufficient measurement time. Otherwise, absence is confirmed if the detected counts are below the critical level without exceeding the maximum shielding.

ACX: Absence Confirmation eXperimental Device

We have developed a prototype device to demonstrate the proposed verification protocol. The ACX (Absence Confirmation eXperimental) device is based on a Raspberry Pi computer with a 7-inch touchscreen display for user input, housed in a durable Pelican case (Figure 3). A rechargeable power-over-ethernet (POE) battery contained within the case supplies power to the computer and an external gamma-ray detector which connects via ethernet. For demonstration and testing, we used a collimated 2-inch Mirion/Canberra NaI scintillator (Model 802) connected to an Osprey Digital MCA Tube Base. We designed the device with minimal user-accessible inputs/outputs, including a recharging port, ethernet port, and universal power switch.

Figure 3: Absence confirmation device with sample screenshots. The ACX (Absence Confirmation eXperimental) device is shown connected to a collimated NaI detector. A custom GUI guides the inspector through the verification protocol. The start screen is shown in the upper-right, which can be toggled to operate with special nuclear material or laboratory check sources. In the lower-right are two sample screenshots of the GUI at various steps during the protocol.

Taking full advantage of the touchscreen, we have developed a custom graphic user interface (GUI) which guides the user through the verification protocol. A single Python code handles the GUI and performs all necessary data acquisition and analysis. A video demonstration of the verification protocol and GUI can be found at youtu.be/JuNA6D4kGe4. The code supports two modes: a laboratory demonstration with check sources or a real inspection with special nuclear materials. To initiate a measurement campaign, the start screen asks the user to input the agreed upon thresholds (in terms of mass for special nuclear material or activity for check sources), the measurement time, and the level of confidence in the inspection result. For each step of the protocol, the device instructs the user to position/remove the calibration source, reference source, and inspected objects. During data acquisition, the GUI provides a countdown clock. After data is acquired for a given step, the user has the option to redo the measurement or move on to the next step; at no point can the user deviate from the prescribed order, reducing the possibility of human error. For the calibration and reference steps, an error message is included if the source is too weak to provide a reliable inspection. The GUI also provides the final inspection result (absence confirmed, inconclusive, or anomaly detected); no other information or data is ever revealed to the user. In addition to enforcing the protocol, the GUI provides two options for performing a new inspection: the user may measure a new object using previously acquired background and calibration, or the user may reset all parameters and begin from the start screen.

Since the ACX hardware is commercially available and the software is Python-based, both the host and the inspector would be able to build the same device. They could perform the same measurements with their respective devices, or a device(s) for inspection can be randomly chosen among them. Low-cost components and portability also support manufacturing and ease of deployment. Additionally, we believe our device is sufficiently user-friendly to not require significant training for inspectors. The hardware design could also potentially be adapted to include tamper indicating enclosures (TIEs) and devices (TIDs) to maintain the confidence and chain of custody.

Simulated and Experimental Demonstrations

The applicability of the proposed verification protocol for reference quantities of special nuclear material (1 kg of WPu and 4 kg of HEU) is demonstrated using MCNP simulations. As an example of a possible geometry, we assume spherical shells of WPu and HEU with an outer diameter of 10 cm. For this simulated setup, the distance between the container and the source is 70 cm and the reference source is positioned 140 cm from the detector. We chose a collimated 1 mCi cesium-137 reference source, which produces statistically significant counts for the proposed configuration within minutes. Table 2 provides key metrics and the inspection result for this simulated demonstration.

As a more tangible demonstration, we also examine the viability of the verification protocol and the analysis of the ACX experimentally using standard laboratory check sources. We use barium-133 (302.9 keV and 356.0 keV) and cobalt-60 (1173.2 keV) as substitutes for plutonium and uranium, respectively. The fundamental detection algorithm is unchanged; the only parameters that must be modified in order to switch between measurements in the field versus the laboratory are the regions of interest for the two relevant isotopes, the corresponding attenuation coefficients, and the threshold activities to indicate an anomaly. As seen in the image of the ACX device in Figure 3, we use a collimated Mirion/Canberra NaI detector (Model 802) connected to an Osprey Digital MCA Tube Base and a reduced standoff distance of 20 cm in order to expedite the measurements. The results of an experimental demonstration of the verification protocol are summarized in Table 3.

Table 2: Simulated demonstration for an inspection using ten-minute measurements for each step of the verification protocol. In both cases, a spherical shell of special nuclear material is shielded by another shell of lead. The time-to-detection and estimated equivalent shielding (due to the nuclear material and external lead, combined) are shown. For the simulated ten-minute measurement, the maximum allowable equivalent shielding is also reported. Note that the only information revealed by the system is the inspection outcome.

	Field Setup (Simulated)	
Measurement Time	600 seconds	
Standoff distance	70 cm	
Isotope	**Pu-239**	**U-238**
Mass	0.93 kg	0.28 kg
SNM shell thickness	1.7 mm	7.8 mm
External lead shielding thickness	12.7 mm	12.7 mm
Region of Interest	300–500 keV	950–1050 keV
Inspection outcome	**Anomaly detected**	**Anomaly detected**
Time to detection	0.03 seconds	1046 seconds
Estimated shielding (lead-equivalent)	17.4 mm	30.1 mm
Shielding limit (lead-equivalent)	43.0 mm	24.9 mm

Table 3: Experimental demonstration for an inspection using five-minute measurements for each step of the verification protocol. The time-to-detection for the current configuration and the maximum allowable shielding for the five-minute measurement are tabulated; if the shielding exceeds this limit, the situation may be "inconclusive" and a longer measurement time could be considered by the inspector and host parties. Note that the only information revealed by the system is the inspection outcome.

	Lab Setup (Experimental)	
Measurement Time	300 seconds	
Standoff distance	20 cm	
Isotope	**Ba-133**	**Co-60**
Activity	1.4 μCi	0.9 μCi
Lead shielding thickness	12.7 mm	12.7 mm
Region of Interest	233–426 keV	1093–1253 keV
Inspection outcome	**Anomaly detected**	**Anomaly detected**
Time to detection	162 seconds	1.4 seconds
Shielding limit	13.6 mm	66.4 mm

Discussion

Current arms-control agreements impose limits on the number of deployed strategic nuclear weapons, while future agreements may include all warheads, including those in storage and slated for dismantlement. In a verification regime based on absence measurements, no weapons should ever be part of an inspection, and safety and security concerns would therefore be dramatically reduced. However, following the proposition that all items declared as treaty-accountable by the host are accepted as such, methods would be required to confirm the absence of a warhead when ambiguities arise.

We have proposed a protocol for confirming the absence of nuclear warheads using only passive gamma-ray measurements. The protocol consists of five basic steps, inclusive of standard background acquisition and detector calibration. The only non-standard requirement is the requirement of a check source with an activity in the 1 mCi range. This reference source is used to estimate the lead-equivalent thickness of shielding present in an inspected object, which helps differentiate between absence confirmation and an inconclusive inspection result.

Our simulation results show that the absence of a threshold quantity of plutonium or uranium can be confirmed within minutes, even if a lightly shielded container is inspected. We have also demonstrated the protocol experimentally in a small-scale experiment using laboratory check sources as stand-ins for special nuclear material and developed a prototype device for performing the proposed protocol. The hardware is all commercially available and the software for controlling the graphic user interface and performing the necessary analysis is all Python-based, so the device can be readily manufactured. The device is designed to enable further evaluation of the viability of the overall verification approach, in addition to supporting possible domestic or international inspection exercises. Field-testing of such a system could help develop the concept further and enable red-teaming of the proposed verification protocol.

Endnotes

[1]Yan Jie and Alexander Glaser, "Nuclear Warhead Verification: A Review of Attribute and Template Systems," *Science & Global Security,* 23 (3), 2015.

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

[3]Consistent with this approach and for similar reasons, a recent report published by the International Partnership for Disarmament Verification (IPNDV) introduced the concept of "items declared as weapons." *Working Group 4: Verification of Nuclear Weapons Declarations*, International Partnership for Disarmament Verification, April 2020.

[4]*Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms* ("New START"), April 2010; *Radiation Detection Equipment: An Arms Control Verification Tool*, Product No. 211P, Defense Threat Reduction Agency, Fort Belvoir, VA, October 2011.

[5]For example, the host may not want to reveal the total background (gamma or neutron) radiation level in a certain facility; such a concern could be addressed with simple information barriers or by conducting the measurement in a separate building or environment.

[6]Since we consider the gamma emissions of U-238 to be indicative of a uranium-based warhead, "trainers" composed of natural or depleted uranium would also have to be declared as treaty-accountable items, unless the host can otherwise demonstrate that they ought to be excluded from the count, such as by visual inspection.

[7]Ron J. McConn Jr., et al., *Compendium of Material Composition Data for Radiation Transport Modeling,* PIET-43741-TM-963, PNNL-15870 Rev. 1, Pacific Northwest National Laboratory, Richland, WA, 2011.

[8]Steve Fetter, Valery A. Frolov, Marvin Miller, Robert Mozley, Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Z. Sagdeev, "Detecting Nuclear Warheads," *Science & Global Security,* 1, 1990.

[9]*Restricted Data Declassification Decisions 1946 To the Present (RDD-8),* U.S. Department of Energy, Washington, DC, 2002.

[10]*Plutonium Pit Production,* National Nuclear Security Administration, U.S. Department of Energy, Washington, DC, 2020.

[11]Since we have assumed axially symmetric objects, throughout this paper, we report shielding as the thickness of lead-equivalent material measured from the center of the object to the detector.

[12]Further detail on how the acquired measurements are analyzed to yield the inspection result can be found in Algorithm 1 of E. Lepowsky, J. Jeon, and A. Glaser, "Confirming the Absence of Nuclear Warheads via Passive Gamma-Ray Measurements," *Nuclear Instruments and Methods in Physics Research A,* 990, 2021.