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Ceci N'est Pas Une Bombe: Lessons from a Field Experiment Using Neutron and Gamma Measurements to Confirm the Absence of Nuclear Weapons

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ABSTRACT
In March 2023, the UN Institute for Disarmament Research held a verification experiment that included a mockup onsite inspection at a former military facility in the municipality of Menzingen, Switzerland. The experiment included a visit to the site by an inspection team, accompanied by the host team. Among other activities, radiation measurements were used to confirm the non-nuclear nature of selected items stored onsite. In this paper, we discuss the neutron and gamma measurement systems used during the experiment and the inspection protocols followed to confirm the absence of nuclear weapons. Results from the experiment and a laboratory reproduction are presented, before concluding with lessons learned for how absence-confirmation measurements can help support verification of future arms control agreements.

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Background

Nuclear arms control is in crisis, and it is currently difficult to anticipate what future bilateral or multilateral agreements could look like and what their objectives might be. Possible frameworks could include reductions with verified warhead dismantlements, limits on the total stockpiles of nuclear weapons, or approaches that avoid warhead inspections altogether.[1] In many, if not all, of these scenarios, it's plausible that inspection approaches would benefit from the ability to confirm the absence of nuclear weapons at an inspected site or within specified areas on that site. In fact, New START has pioneered some of these techniques to confirm that an "object located on the front section [of a ballistic missile] and declared by the in-country escort to be a non-nuclear object" is in fact non-nuclear and therefore not treaty accountable.[2] New START does not, however, cover warheads in storage and relies on neutron measurements only, which can indicate the presence of plutonium but cannot be used for

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uranium-only weapons or weapon components because neutron emissions from relevant uranium isotopes are orders of magnitude lower.[3] To support future treaty provisions based on the absence of nuclear weapons and, in particular, to further explore the concept of deferred verification,[4] the UN Institute for Disarmament Research (UNIDIR) organized the Menzingen Verification Experiment in partnership with Spiez Laboratory and Princeton University's Program on Science and Global Security. The project was supported by the governments of Switzerland, Norway, and the Netherlands. Logistical support was provided by the Swiss Armed Forces.

This paper focuses on the radiation measurements that were conducted as part of the experiment and performed in a series of bunkers in the south-eastern area of a former military base in the municipality of Menzingen, Switzerland (Figure 1).[5] The scenario developed by UNIDIR was based on the assumption that some containers had been previously "flagged" by inspectors for further inspection; these containers had been moved to these dedicated bunkers for radiation measurements. In order to test procedures for cases where anomalies are detected, gamma and neutron sources were provided and installed by Spiez Laboratory in some of these containers.

Two bunkers (201, 202) had previously been prepared for passive neutron measurements, one of them containing a containerized californium-252 spontaneous neutron source, while the container in the second bunker was empty. The neutron bunkers were inspected using a commercial neutron detector. Two additional bunkers (204, 205) had been prepared for gamma measurements, one of them containing containerized depleted-uranium projectiles,[6] while the container in the second bunker was again empty. Inspections of the gamma bunkers used a custom-developed device and inspection protocol,

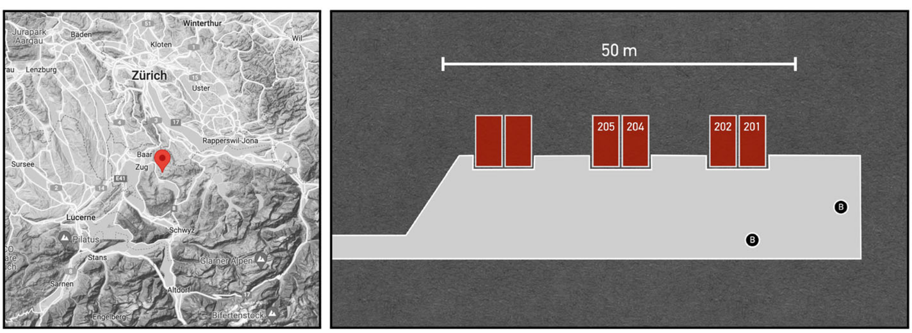

Figure 1. Location of the site in the municipality of Menzingen, Switzerland. Radiation measurements were conducted in a series of bunkers (201, 202, 204, 205) in the south-eastern section of the base (47.157522, 8.585728). Locations for neutron background measurements are indicated (B); after completion of the experiment, and after the removal of the sources from the bunkers, an additional background measurement was conducted in bunker 201, where neutron radiation levels were about ten times lower. Source: Google Maps (left).

which are described in more detail below. The order of the empty and source-containing bunkers was unknown to the inspectors, and the goal was to correctly identify "cold" and "hot" bunkers without directly accessing the inspected containers.

Systems and protocols

As part of the experiment, the organizers provided the host and inspector teams with a script specifying the inspection protocol. Worksheets (reproduced in the Appendix) were used to record relevant values acquired during the radiation measurements. For the two neutron bunkers, a polyethylene-moderated helium-3 proportional counter (Berthold LB 6414, Figure 2, right) was used to provide the count rate averaged over a prescribed period of time, previously agreed upon by the host and the inspector. The neutron detector was positioned on a tripod such that the helium-3 tube was at approximately the same height as the center of the inspected container. The measurements largely followed the New START inspection protocol consisting of a background measurement and a measurement of the inspected container. Although non-ideal, and as further discussed below, the neutron background was acquired in the open, just outside the bunker (see Figure 1, right) because the containers themselves could not be moved from their positions. The threshold for anomaly detection was set using the "four-sigma" test, i.e., an anomaly was recorded when the counts observed during the inspection exceeded the background by four standard deviations.

Verification of the gamma bunkers followed the inspection protocol previously proposed for the Absence Confirmation Experimental Device (ACX),[7] using a revised version of the original prototype. The device is comprised of a Raspberry Pi single-board computer and a 7-inch display installed in a portable Pelican case. A rechargeable power-over-ethernet battery contained within the case supplies power to the computer and the

Figure 2. View of the four bunkers used for the radiation measurements (left). The detector used for the neutron measurements (Berthold LB 6414) uses a polyethylene-moderated helium-3 tube and is optimized for plutonium search applications (right). Source: Pavel Podvig and Spiez Laboratory.

external detector, which connects via ethernet to the device. We used a collimated 2-inch Mirion/Canberra NaI scintillator (Model 802) connected to an Osprey Digital MCA Tube Base.[8] The second-generation device (ACX2) has minimal user-accessible inputs/outputs, including an ethernet port, a power button, and a USB port to connect a numeric keypad. A custom Python script controls the detector and guides the user through the protocol steps in a shell-based application. No measurement data are saved to disk. Figure 3 shows some participants performing gamma measurements with the ACX2 device during the verification experiment.

The protocol for the gamma measurements begins with background acquisition and detector calibration. A strong reference source (0.48 mCi cesium-137) is then placed at a suitable distance in direct view of the detector such that the inspected container can later be placed between the detector and this source. By comparing the signal with and without the container, the reference source is used to estimate the shielding introduced by the inspected container.[9] In the final step of the inspection, the reference source is removed so that emissions from the inspected container itself can be measured. Overall, seven measurement values are collected in different regions of interest. These regions (300–500 keV for Pu-239 and 950–1,050 keV for U-238) were selected for having the highest intensity and most characteristic gamma emissions.[10] The measurement values determine the ultimate inspection result: absence of plutonium and uranium confirmed or anomaly detected. The inspection result can also be inconclusive if too much shielding was present or if the measurement time was too short to yield an unambiguous outcome.

Inspection results

The most straightforward inspection results were obtained for those bunkers where sources were present. In both cases, the threshold values

Figure 3. Participants of the Menzingen Verification Experiment. Left: Host (yellow vests) and inspector (orange vests) teams discussing the operation of the Absence Confirmation Experimental (ACX2) device. Right: Participants set up the sodium iodide detector for passive gamma ray and transmission measurements of the inspected container. Source: Pavel Podvig.

were clearly exceeded. In the case of the neutron measurements, which used a californium-252 source emitting on the order of 90,000–95,000 n/s, the total counts acquired during the inspection exceeded the threshold value by more than two orders of magnitude (4,485 counts vs. 28 counts for a measurement time of 150 seconds; Bunker 202). Similarly, in the case of the gamma measurements, 1,744 counts were observed for a measurement time of 300 seconds during the inspection of the container with depleted uranium (Bunker 205), while only 52 counts were sufficient to trigger an anomaly for uranium. The depleted uranium projectiles used during these measurements amounted to about 800 g of uranium-238, which is equivalent to 11–12 kg of weapon-grade uranium with 7% U-238. For both the neutron and gamma measurements, the containers introduced only negligible amounts of shielding and no other shielding was present.

The results acquired for the empty bunkers are more complex—and therefore perhaps also more interesting.

Neutron measurements; empty container

During the inspection of the empty container, the total counts exceeded the previously established threshold value by a statistically significant amount (45 vs. 28 counts for a measurement time of 150 seconds; Bunker 201). The inspection report, therefore, noted an anomaly. Once the experiment had concluded and all sources been removed from the bunkers, we were able to perform additional measurements in an effort to explain the data. Indeed, only 1.5 counts were observed in Bunker 201 compared to 45 counts during the inspection. In hindsight, we concluded that neutrons had been leaking from the neighboring Bunker 202, where a source was located, interfering with the measurements in Bunker 201 during the inspection. It is worth noting that this would have been irrelevant had we been able to conduct the background measurement inside the bunker itself (with the inspected container absent); it is also worth noting that the neutron background in the bunker was almost ten times lower than the background measured outside.

Gamma measurements; empty container

The measurement in Bunker 204 correctly confirmed the absence of uranium (and plutonium) sources in the inspected container. When reviewing the values of the container-only measurements (Lines 6a–6c in the respective worksheet), the value for the region of interest for plutonium stands out: here, 130 counts were recorded above the background measurement of 1,971 counts (for a measurement time of 450 seconds; Bunker 204). While this increase is not statistically impossible, the most plausible explanation is the way that the background measurement was conducted. As the container could not be removed from the bunker, we rotated the shielded detector by 90°, orienting it toward the bunker wall.[11] During the inspection, however, the detector was oriented toward the bunker doors. It's likely, but cannot be confirmed with certainty at this time, that the background levels were measurably different for these two orientations; in fact, the difference corresponds to an increase of only about 7% (from 1,971 counts to 2,101 counts, or from 4.38 cps to 4.67 cps). It is worth noting that even such a slight increase in background is potentially problematic. In this particular case, the system would have indicated an anomaly had the counts in the region of interest for plutonium exceeded a value of 146 counts (Line 7b in the worksheet). In other words, we came close to a false-positive inspection outcome.

Finally, we also note that detector drift could have added additional measurement error. Indeed, we used a non-temperature-stabilized detector for this experiment, moved the equipment from room temperature to an ambient temperature of about 5 °C (40 °F), and measured for more than two hours. We don't see clear evidence, however, that detector drift affected the results.

Laboratory analog for gamma measurements

Due to security limitations, the spectra acquired during the Menzingen experiment could not be saved or taken offsite. As a means for visualizing the measurements, we later established a laboratory analog for the gamma measurement at Princeton Plasma Physics Laboratory (PPPL). Two-inch depleted-uranium (DU) cubes, a 0.1 mCi Cs-137 reference source, and metal plates (aluminum or steel) were configured to provide representative measurements. The experimental setup is shown in Figure 4.

The spectra acquired in 10-minute measurements are shown in Figure 5. By factoring in the background level, measurement time, mass of DU, and the effect of self-shielding in the DU, we can scale the results to approximately correspond to the scenario encountered during the Menzingen experiment. The Menzingen setup had 16% of the DU (by mass) present at PPPL, which was measured for half the time. Additionally, the projectiles used in Menzingen exhibit less self-shielding than the two-inch cubes available at PPPL. According to a simple Monte Carlo calculation, 2.1-times and 1.9-times more gammas escape from the projectile for the uranium and plutonium regions of interest, respectively.[12] With these scaling factors, the PPPL counts were within about 10% (uranium region of interest) and 25% (plutonium region of interest) of the Menzingen counts. This approximate agreement demonstrates that we can reasonably predict the expected counts from the verification experiment, especially considering several unknown experimental conditions, which cannot be reproduced in this simple analysis.

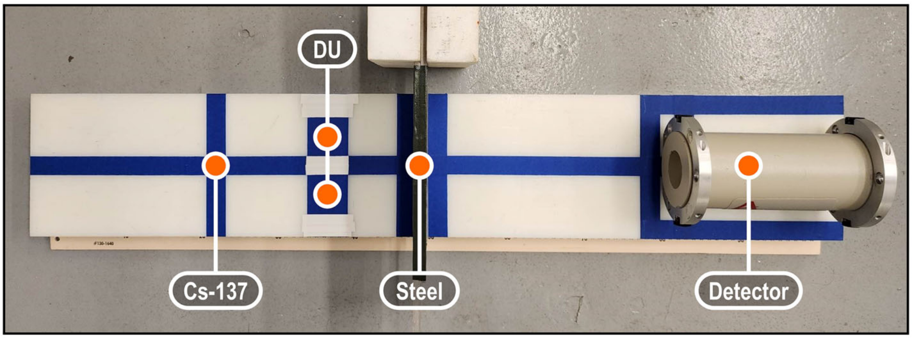

Figure 4. Laboratory setup as an analog for the Menzingen measurements. The collimated sodium iodide detector is positioned 40 cm from two DU cubes, which are separated by approximately 2–3 cm. A half-inch thick plate of steel (or aluminum) is positioned 10 cm in front of the DU, and the Cs-137 reference source is positioned 15 cm behind the DU. The gap in between the DU cubes allows the Cs-137 to be seen by the detector to perform a transmission measurement on the steel or aluminum. This is used as a stand-in for a thinner configuration of DU. Source: Eric Lepowsky.

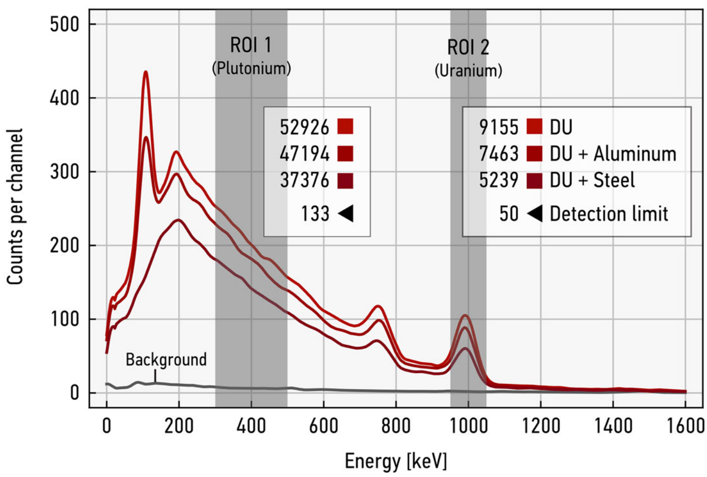

Figure 5. Spectra acquired using the laboratory setup. Background-subtracted spectra of the DU cubes are shown for different types of external shielding. The gray bands indicate the regions of interest for plutonium (300–500 keV) and uranium (950–1,050 keV). For the analysis performed by the ACX2 device, counts are summed over the channels within these regions of interest. The summed counts in the regions of interest for each measurement are indicated. In all cases shown here, the counts far exceed the respective detection limits.

Lessons learned

Despite extensive preparations, which included the development of inspection approaches and laboratory testing of the equipment, we learned a number of new and important lessons during the experiment.

First, and perhaps quite self-evidently, we recognize that possible field conditions must be carefully considered when designing the hardware and software. Ideally, the equipment ought to be tested in environments that closely reproduce the conditions that could be encountered later in the field. In our case, the equipment had to be moved between outdoor and indoor settings multiple times throughout the day and, ultimately, be operated at temperatures far below room temperature. While the temperatures were within the equipment's allowed operating range, detector calibration and drift can pose significant challenges, in particular, for the gamma measurements, which extended over several hours and used a non-temperature-stabilized detector. Even though the equipment ultimately worked as expected, printing calibration parameters, displaying other non-sensitive information to confirm equipment functionality, and allocating additional time for recalibration would have reassured both the inspector and host teams.

With regard to the usefulness of simple radiation measurements to confirm the absence of nuclear weapons, we found that the ACX2 device equipped with a sodium-iodide detector is best suited for uranium detection, less so for plutonium detection. The lower region of interest (300–500 keV), centered around some prominent gammas emitted by plutonium, is triggered when other radiation sources are present, often due to the elevated Compton continuum. While this does not compromise the functionality of the device, it does make it more prone to false-positive results. One way to address this challenge would be to work with a high-resolution detector and identify isotope-specific gamma lines; this would, however, increase the complexity of other aspects of the measurement, both on the software and hardware side. Ultimately, one may conclude that neutron measurements are sufficient for plutonium detection while gamma measurements are most useful for uranium detection, such that coverage is provided by a combination of both.

Finally, and most importantly, the verification experiment highlighted the critical importance of adequate background measurements. As part of New START, such measurements were manageable because the treaty deals with deployed weapons in known configurations, and radiation measurements are generally conducted outdoors. Future agreements may, however, envision fundamentally different inspection environments including, in particular, indoor and "in situ" measurements. These could include measurements on warheads or warhead components in storage or, as in the case of the Menzingen Verification Experiment, confirming the absence of treaty-accountable items in various areas and buildings of an inspected site. During the experiment, we were not able to move containers that were selected for inspection; for this reason, background measurements had to be taken nearby (i.e., just outside the bunker) or with a modified setup (i.e., with a re-oriented detector). Interestingly, and for different reasons, this led to complications for both types of measurements conducted: one measurement indicated an anomaly due to neutron leakage from an adjacent bunker even though the true neutron background in the bunker was ten times lower than the background acquired outside; another measurement produced confusing results for one region of interest and was close to indicating an anomaly. These complications can be avoided entirely if items selected for inspection can be moved as needed—but these aspects ought to be carefully considered when verification protocols are negotiated.

In passing, we note that there are possible noncompliance scenarios that are particularly relevant for absence measurements. The host could, for example, introduce a concealed radiation source during the background measurement so that an inspected item containing plutonium or uranium would later pass the inspection, i.e., produce a false-negative. Given that the host controls the inspection environment, additional safeguards may have to be considered to preclude such deceptive maneuvers.[13] Another challenge, not examined here, will be agreement on criteria for inspectable objects and, in particular, agreement on a minimum size of such objects. For example, there could be concerns that a party stores weapons partly disassembled such that nuclear components are kept in areas not accessible to inspectors. Indeed, in the 1980s, there were proposals to reintroduce such "clip-in" or "insertable" warheads into the U.S. stockpile—a prospect considered an "arms control nightmare" by some analysts.[14] Ultimately, if the absence of nuclear weapons is to be confirmed with some reasonably high confidence, it may be necessary to consider for inspection even relatively small objects and containers.

Overall, there is continued room for improvement and much consideration necessary for such absence-confirmation measurement protocols and equipment, but the experiment demonstrated promise for how it may fit into the larger verification landscape.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Notes

1. M. Göttsche and A. Glaser (eds.), *Toward Nuclear Disarmament: Building Up Transparency and Verification* (Berlin: German Federal Foreign Office, 2021); P. Podvig and J. Rodgers, *Deferred Verification: Verifiable Declarations of Fissile Material Stocks* (Geneva: UNIDIR, 2017).
2. *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.
3. S. Fetter, V. A. Frolov, A. Miller, R. Mozley, O. F. Prilutsky, S. N. Rodionov, and R. Z. Sagdeev, "Detecting Nuclear Warheads," *Science & Global Security* 1, no. 3–4 (1990): 225–253.
4. Deferred verification is a proposed arrangement, in which an initial declaration is verified only at the time when the materials or items that originally contained these materials are eliminated. See P. Podvig and J. Rodgers, 2017, op. cit.
5. The base was operational until 1999 and now hosts a museum, www.mhsz.ch/bloodhound.
6. Uranium-235 only emits low-energy gamma radiation. Despite the small uranium-238 content, highly enriched uranium and weapon-grade uranium (more than 90% U-235) are best detected using gamma radiation from uranium-238, namely, via a prominent gamma line at 1.001 MeV. With appropriate scaling of results, depleted uranium can therefore be used as a stand-in for weapon-grade material.
7. 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).
8. Mirion Technologies, *802 Scintillation Detectors, Datasheet*, 2017; Mirion Technologies, *Osprey*: *Universal Digital MCA Tube Base for Scintillation Spectrometry, Datasheet*, 2017.
9. The protocol, as followed during the experiment, assumes that the transmission measurement with the reference source was aligned with the center of the inspected object. In practice, to make the measurement more robust against positioning, multiple measurements would be preferable, and the inspector should be allowed to choose the locations of those measurements.
10. Selection of the regions of interest is described in detail in E. Lepowsky et al., 2021, op. cit. As lower-energy gammas from uranium-235 are easily shielded, gamma emissions from weapon-grade uranium (90% uranium-235 and higher) are still dominated by the 1.001-MeV line associated with the decay of uranium-238.
11. Another solution (suggested by a reviewer) is a curved shield that spans 180° and can be rotated behind the detector when measuring the container and rotated in front of the detector when collecting background; this will allow the detector to remain stationary for both measurements.
12. For the purposes of this self-shielding approximation, pure uranium-238 was used for the isotopic composition with mono-energetic 1.001 MeV photons spawned uniformly

throughout the solid geometry, and the fraction of emitted gammas was tallied within each region of interest. The simulation was performed using MCNP6.2: C. J. Werner, et al., MCNP6.2 Release Notes, LA-UR-18-20808, New Mexico: Los Alamos National Laboratory, February 2018.

13. One way for the host to build confidence with inspectors is to allow sweeping of the facility with gamma and neutron detectors to establish the background rate at multiple points in the room and identify possible anomalies. Hosts should not find this intrusive if the location is truly empty. This should be done in concert with an inspection of the walls and floor to look for gaps or cavities where sources could be hidden to manipulate the background. Inspectors should request that measurements be made at the center of the room instead of near the walls, making it more difficult for hosts to manipulate the background using sources in an adjacent area.
14. F. Hiatt, "Insertable Nuclear Warheads Could Convert Arms," *The Washington Post*, June 15, 1986; for a related discussion, see A. Glaser, "Toward Verifiable Definitions of a Nuclear Weapon," *Arms Control Today* 53, no. 6 (July/August 2023).

Appendix

Inspection Worksheet for Neutron Measurements (with LB 6414)

Revision 0.6
Menzingen Experiment
March 2023

Date		March 8, 2023	
Local time		14:02	
Location		201	
Inspected item ID		Category B	
Measurement time proposed by host (60–150 seconds)	01	150	seconds
Measurement time chosen by inspector	02	150	seconds
Line 02 must be ≥ Line 01 but ≤ 150 seconds			
Average background count rate	03a	0.085	cps
Total background counts (B = Line 03a x Line 02)	03b	13	counts
Rounded up to next integer			
Reference number (R) with R = B + 4 x √B	04	28	counts
Rounded up to next integer			
Distance from detector to center of item	05	60	cm
Line 05 must be ≤ 70 cm			
Average count rate during inspection	06a	0.300	cps
Total counts acquired during inspection (Line 06a x Line 02)	06b	45	counts
Rounded down to previous integer			
Check box if Line 06b ≤ Line 04			Non-nuclear object confirmed
Check box if Line 06b > Line 04		X	Anomaly detected

Notes

Inspection Worksheet for Neutron Measurements (with LB 6414)

Revision 0.6
Menzingen Experiment
March 2023

Date		March 8, 2023	
Local time		13:32	
Location		202	
Inspected item ID		Category B	
Measurement time proposed by host (60–150 seconds)	01	150	seconds
Measurement time chosen by inspector	02	150	seconds
Line 02 must be ≥ Line 01 but ≤ 150 seconds			
Average background count rate	03a	0.085	cps
Total background counts (B = Line 03a x Line 02)	03b	13	counts
Rounded up to next integer			
Reference number (R) with R = B + 4 x √B	04	28	counts
Rounded up to next integer			
Distance from detector to center of item	05	60	cm
Line 05 must be ≤ 70 cm			
Average count rate during inspection	06a	29.9	cps
Total counts acquired during inspection (Line 06a x Line 02)	06b	4485	counts
Rounded down to previous integer			
Check box if Line 06b ≤ Line 04			Non-nuclear object confirmed
Check box if Line 06b > Line 04		X	Anomaly detected

Notes

Inspection Worksheet for Gamma Measurements (with ACX 2)

Revision 0.6
Menzingen Experiment
March 2023

Date		March 8, 2023	
Local time		14:30	
Location		204	
Inspected item ID		Category C	
Measurement time proposed by host	01	450	seconds
Measurement time chosen by inspector (and used)	02	450	seconds
Line 02 must be ≥ Line 01			
Background, Region of Interest for plutonium	03a	1971	counts
Background, Region of Interest for uranium	03b	318	counts
Distance from detector to center of item	04	48	cm
Line 04 must be ≤ 70 cm			
Reference source (without container)	05a	316370	counts
Reference source (with container)	05b	288337	counts
Container only (ROI for reference source)	06a	0	counts
Container only (ROI for plutonium)	06b	130	counts
Container only (ROI for uranium)	06c	0	counts
Critical limit (ROI for plutonium)	07a	146	counts
Critical limit (ROI for uranium)	07b	58	counts
Estimated thickness of shielding, lead-equivalent	08	1	mm
Maximum shielding thickness (ROI for plutonium)	09a	27	mm
Maximum shielding thickness (ROI for uranium)	09b	24	mm

INSPECTION RESULT

- [X] Absence confirmed
- [ ] Inconclusive
- [ ] Anomaly detected

Notes

Inspection Worksheet for Gamma Measurements (with ACX 2)

Revision 0.6
Menzingen Experiment
March 2023

Date		March 8, 2023	
Local time		16:30	
Location		205	
Inspected item ID		Category C	
Measurement time proposed by host	01	300	seconds
Measurement time chosen by inspector (and used)	02	300	seconds
Line 02 must be ≥ Line 01			
Background, Region of Interest for plutonium	03a	1767	counts
Background, Region of Interest for uranium	03b	255	counts
Distance from detector to center of item	04	40	cm
Line 04 must be ≤ 70 cm			
Reference source (without container)	05a	226735	counts
Reference source (with container)	05b	177113	counts
Container only (ROI for reference source)	06a	2275	counts
Container only (ROI for plutonium)	06b	10603	counts
Container only (ROI for uranium)	06c	1744	counts
Critical limit (ROI for plutonium)	07a	138	counts
Critical limit (ROI for uranium)	07b	52	counts
Estimated thickness of shielding, lead-equivalent	08	1	mm
Maximum shielding thickness (ROI for plutonium)	09a	26	mm
Maximum shielding thickness (ROI for uranium)	09b	19	mm

INSPECTION RESULT

- [ ] Absence confirmed
- [ ] Inconclusive
- [X] Anomaly detected

Notes