Confirming the Absence of Nuclear Weapons

Neutron and Gamma Measurements During a Verification Experiment in Switzerland

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Abstract. In March 2023, the UN Institute of Disarmament Research held a verification experiment that included a mockup onsite inspection at a former military facility in Menzingen, Switzerland. The project was supported by the governments of Switzerland, Norway, and the Netherlands. Logistical support was provided by the Swiss Armed Forces. 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 items located inside the object of verification. In this paper, we discuss the gamma and neutron measurement systems used during the experiment and the inspection protocols followed to confirm the absence of nuclear weapons.

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 uranium-only weapons or weapon components.

To support future treaty provisions based on the absence of nuclear weapons and, in particular, to further explore the concept of deferred verification, the UN Institute of Disarmament Research (UNIDIR) organized the Menzingen Verification Experiment in partnership with the Swiss Army, Spiez Laboratory, and Princeton University's

Program on Science and Global Security. The experiment provided an opportunity to test relevant procedures at a declared storage site. This paper focuses on the radiation measurements that were conducted as part of this experiment; the broader scope of the experiment are described in greater details in other contributions at this conference.[3]

The radiation measurements were conducted in a series of bunkers in the south-eastern area of the base (Figure 1). 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 polyethylene-moderated helium-3 neutron detector. Two additional bunkers (204, 205) had been prepared for gamma measurements, one of them containing containerized depleted-uranium projectiles,[4] while the container in the second bunker was again empty. Inspections of the gamma bunkers used a custom-developed device and inspection protocol, 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.

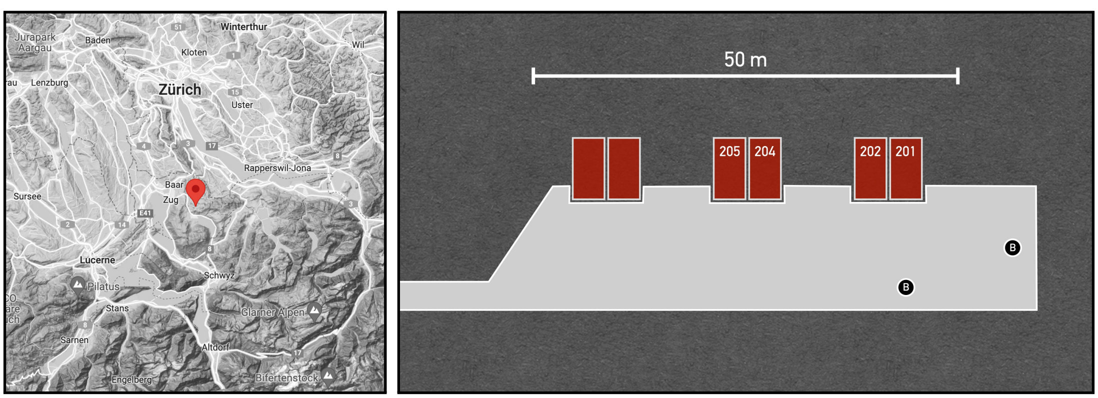

Figure 1: Location of the site in the municipality of Menzingen, Switzerland. Radiation measurements were conducted in a series of bunkers (201, 202, 204, 205) in the south-eastern section of the base (47.157522, 8.585728). Locations for neutron background measurements are indicated (B); after completion 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).*

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 Figure 6) 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 previously agreed period of time. 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.

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.*

Verification of the gamma bunkers followed the inspection protocol previously proposed for the Absence Confirmation Device (ACX),[5] using a revised version of the original prototype. The ACX 2.0 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 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.[6] The device has minimal user-accessible inputs/outputs, including an ethernet port, 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.

The protocol begins with background acquisition and detector calibration. A strong (cesium-137) reference source 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. 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 (see inspection worksheet for gamma measurements in Figure 6). These values are used to estimate the effective shielding thickness introduced by the inspected container and to 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 were present or the measurement time was too short to yield a conclusive outcome.

Figure 3: Participants of the Menzingen Inspection Experiment. Left: Host (yellow vests) and inspector (orange vests) teams discussing the operation of the Absence Confirmation Experimental (ACX 2.0) device. Right: Participants set up the sodium iodide detector for passive gamma ray and transmission measurements of the inspected container. *Source: Pavel Podvig.*

Inspection Results

The most straightforward inspection results were obtained for those bunkers where sources were present. In both cases, the threshold values 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 (4485 counts vs. 28 counts, Figure 6, Location 202). Similarly, in the case of the gamma measurements, which used depleted-uranium projectiles summing to about 800 grams of uranium-238 (equivalent to 11–12 kilograms of weapon-grade uranium with 7% U-238), 1744 counts were observed during the inspection of the container with depleted uranium, while only 52 counts were sufficient to trigger an anomaly for uranium. 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 small, but statistically significant, amount (45 vs. 28 counts; Figure 6, Location 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 1971 counts. While this increase is statistically not impossible, the most plausible explanation is due to the way the background measurement was conducted. As the container could not be removed from the bunker, we rotated the shielded detector by 90 degrees, orienting it toward the bunker wall. 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 1971 counts to 2101 counts, or from 4.38 cps to 4.67 cps, for a measurement time of 450 seconds). 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 some 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 established a laboratory analog for the gamma measurement at Princeton Plasma Physics Laboratory. 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.

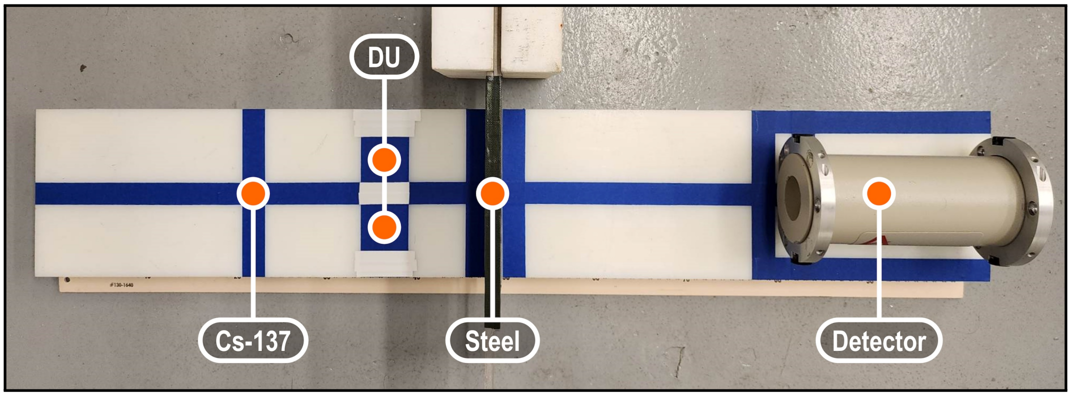

Figure 4: Laboratory setup as an analog for the Menzingen measurements. The collimated sodium iodide detector is positioned 40 cm from two DU cubes, which are separated by approximately 2–3 cm. A half-inch thick plate of steel (or aluminum) is positioned 10 cm in front of the DU, and the Cs-137 reference 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.*

The spectra acquired in 10-minute measurements are shown in Figure 5. By applying the same data analysis from the ACX 2.0 device, we can determine the respective values for the gamma worksheet. Furthermore, 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, according to a simple Monte Carlo calculation, while 52.5% of 1.001 MeV photons escape from the projectile shape, only 25.6% escape from the two-inch cube.[7] With these non-exhaustive scaling factors, the PPPL counts for the uranium and plutonium regions of interest were within 14% and 18% of the Menzingen counts, respectively. This approximate agreement is remarkably reassuring, demonstrating that we can reasonably predict the expected counts from the verification experiment, particularly considering the several *unknown* factors, which are not considered in this simple analysis.

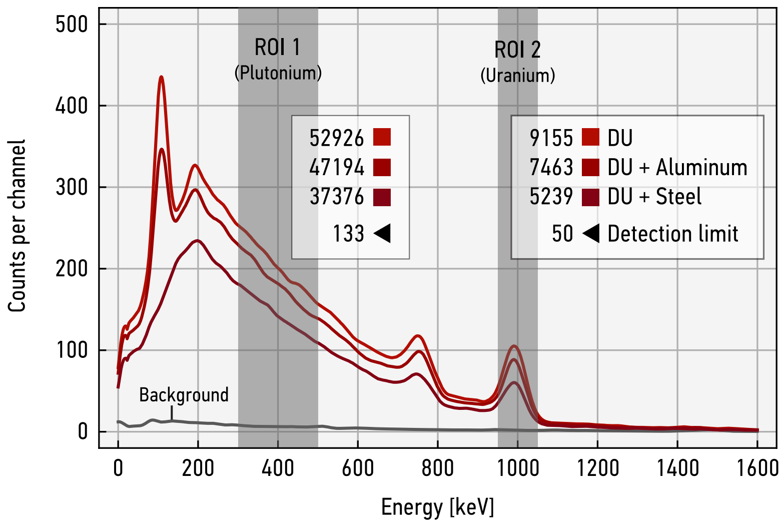

Figure 5: Spectra acquired using the laboratory setup. Background-subtracted spectra of the DU cubes are shown for different types of external shielding. The gray bands indicate the regions of interest for plutonium (300–500 keV) and uranium (950–1050 keV). For the analysis performed by the ACX 2.0 device, counts are summed over the channels within these regions of interest. 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 effectively 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 ACX (2.0) 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 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 some 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 non-compliance scenarios that are particularly relevant for absence measurements, where 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 attacks.

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.

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

Figure 6: Worksheets from the Menzingen Verification Experiment.

Acknowledgements

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Endnotes

[1]M. Göttsche and A. Glaser (eds.), *Toward Nuclear Disarmament: Building Up Transparency and Verification*, German Federal Foreign Office, Berlin, May 2021; Pavel Podvig and Joseph Rodgers, *Deferred Verification: Verifiable Declarations of Fissile Material Stocks*, UNIDIR, Geneva, 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]Pavel Podvig, "Verifying the Absence of Nuclear Weapons: Results of a Field Exercise," *INMM/ESARDA Joint Annual Meeting,* Vienna, Austria, May 2023.

[4]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.

[5]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.

[6]*802 Scintillation Detectors, Datasheet*, Mirion Technologies, 2017; *Osprey: Universal Digital MCA Tube Base for Scintillation Spectrometry, Datasheet*, Mirion Technologies, 2017.

[7]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. The simulation was performed using MCNP 6.2: *MCNP6.2 Release Notes,* LA-UR-18-20808, Los Alamos National Laboratory, New Mexico, February 2018.

(Revision 0)