Virtual Gamma-ray Spectrometry for Template-Matching Nuclear Warhead Verification

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ABSTRACT. Gamma-ray spectrometry has been successfully employed to identify unique items containing special nuclear materials using both attribute and template approaches. Based on an analysis of measured gamma spectra, attribute measurements determine selected characteristics of the item (e.g. an isotopic ratio or a minimum mass); template measurements compare the spectrum against a "template" that has been previously generated with a trusted reference item. High-resolution (HPGe) detectors are essential, in particular, for attribute measurements in order to resolve isotopic-specific features in the spectra. In this analysis, we use the Monte Carlo particle transport code MCNP to model simple material-detector configurations. We examine a series of basic diversion scenarios and assess the viability of gamma-ray spectrometry for verification applications. We examine, in particular, also the use of low-resolution (sodium-iodide scintillation) detectors for this purpose: these detectors are inadequate for attribute-measurements, but—depending on the requirements—may be viable for template systems. The lack of detail in the data acquired with these detectors may help protect classified information or reduce the requirements for information barriers.

Background

Current nuclear arms-control agreements between the United States and Russia limit the number of deployed strategic nuclear weapons each party can have. In the future, however, nuclear arms-control agreements will most likely also place limits on the number of nuclear weapons and warheads that a country can maintain in its arsenal. Such agreements would require the inspection and verification of warheads that are in storage and queued for dismantlement. To accomplish this task, viable verification approaches must be available to confirm the authenticity of nuclear components while also protecting classified information. One such approach would be to analyze the gamma spectrum originating from an item identified for verification, and—through the use of an information barrier—only confirm or deny the identity of the item as a valid nuclear component without otherwise revealing any information about the item.

Several information barriers have been developed based on the attribute method, whereby a given set of attributes, such as mass thresholds and isotopic ratios, are used to characterize these components. Since 2007, the United Kingdom and Norway have been working on an initiative to develop and demonstrate such a system.[1]

To address some of the shortcomings of the attribute method, a second approach has been developed. Known as the template-matching approach, this technique compares a radiation signature (for example, the gamma spectrum) of an inspected item to a reference item. The Trusted Radiation Inspection System (TRIS) developed at Sandia National Laboratories is the most prominent system in this category.[2] Unlike the attribute approach, the template approach does not seek to determine absolute characteristics of the inspected item, such as plutonium mass or isotopics. Instead, the method only reveals significant differences between two items without "knowing" what the origin for these differences are. While passive gamma spectrometry is generally unsuited for determining the amount of fissile material in a nuclear component of unknown geometry due to self-shielding effects,[3] it can be used to obtain a "minimum mass estimate" of an inspected item.[4] Here, we examine conditions under which the technique is able to detect significant differences in the mass or the geometry of special nuclear material in simple configurations using simulated gamma spectra.

Computer Model and Benchmark with Experimental Data

We use extensive MCNP Monte Carlo simulations to determine the expected performance of the inspection system. In order to validate these simulations, we draw on the high-quality SINBAD-2013.12 benchmark data for the so-called beryllium-reflected plutonium (BeRP) ball.[5] The dataset is part of a larger collection available from the Radiation Safety Information Computational Center (RSICC).[6] The bare BeRP ball is a solid 4484-gram sphere of alpha-phase, weapon-grade plutonium (93.7 wt% Pu-239) enclosed in a thin steel casing. The ball was fabricated in 1980 and contains about 0.25 wt% of americium-241 today. The SINBAD exercise carried out in January 2009 used a High-Purity Germanium (HPGe) detector for all gamma measurements.[7] Figure 1 shows the experimental setup of the plutonium source and the detector.

Our MCNP model of the plutonium ball includes a total of 364 plutonium and americium lines.[8] The simplified detector model includes the germanium crystal, shielding material, and the aluminum housing. The crystal has diameter of 8.9 cm and a length of 11.1 cm. In the original experiment, the detector was placed at a distance of 2 meters from the source covering only a very small solid angle. In order to increase the efficiency of the Monte Carlo simulations, we place a large number of identical detectors on a spherical surface with the same two-meter radius. Particles that reach one of the detectors but leave it without interacting are terminated by the simulation in order

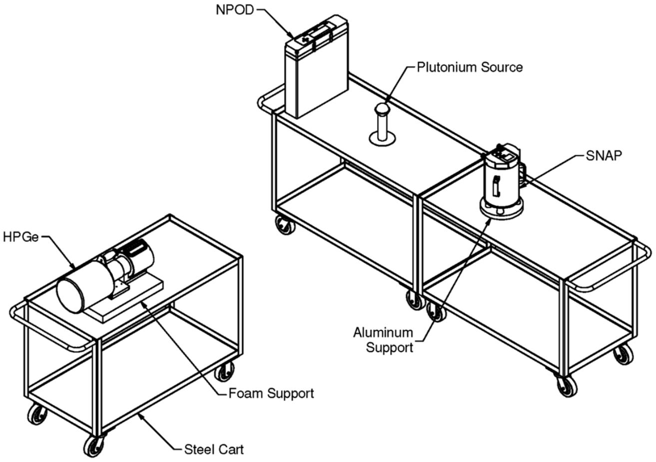

Figure 1: Experimental setup of plutonium source and detectors (Mattingly, 2009). Only the data for the high-purity germanium (HPGe) gamma detector is modeled and analyzed for this study.

to avoid the possibility of an unrealistic interaction in another detector. The modified "Vogel's Method" is a particularly elegant and efficient way of evenly distributing points on a spherical surface.[9] Figure 2 shows the positions of 1000 virtual detectors used in our simulations, effectively increasing the efficiency of the simulations by the same factor. In order to model the detector response, the standard MCNP F8 Tally is used. Detector-specific Gaussian energy broadening is applied to each tally bin post-simulation using characteristic full-width half-maximum functions.[10] By comparison with the experimental data, we find for the detector used in the SINBAD campaign:

$$\mathrm{FWHM}_1(E) \approx 0.00125\sqrt{E(\mathrm{MeV}) + 0.00090\left(E(\mathrm{MeV})\right)^2}$$

Similarly, we find for a NaI scintillation detector used in our laboratory:[11]

$$\mathrm{FWHM}_2(E) \approx 0.05086\sqrt{E(\mathrm{MeV}) + 0.30486\left(E(\mathrm{MeV})\right)^2}$$

For a photon energy of 660 keV, this corresponds to a resolution of about 0.3% for the HPGe and about 6.9% for the NaI detector. Figure 6 at the end of the article shows a comparison of the experimental with the simulated HPGe data for two different energy ranges. Overall, all relevant spectral features are well reproduced in the MCNP simulations.

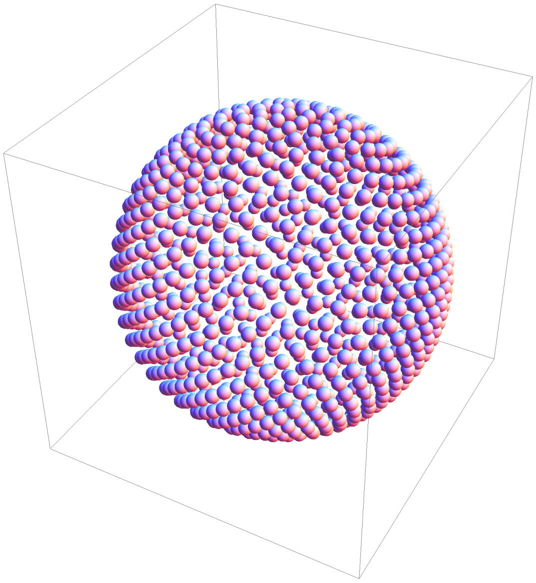

Figure 2: Distributing N points (about) evenly over a sphere using Vogel's method.

Results

We examine a series of basic diversion scenarios from the (bare) BeRP ball illustrated in Figure 3. Scenario Type A tests the sensitivity of the inspection system to material diversions while the outer dimensions of the component remain unchanged. To achieve this, material is gradually removed from the interior of the BeRP ball. Scenario Type B tests the sensitivity of the inspection system to changes in the geometry of the item. Here, we consider hollow plutonium shells with different thicknesses, while the plutonium mass is kept constant. As a consequence, the outside diameter of these shells increases as their thickness decreases.

Agreed criteria are needed to indicate if an item has passed or failed an inspection, i.e., if differences between two items (template and inspected item) are considered significant. Here, we examine two criteria: first, the total count rates, which could indicate removal of material or geometry changes; and second, spectral anomalies, which could indicate substitution of material or other modifications.

Total count rate: A significant difference between the count rate observed in the template measurement and the count rate observed in the inspection is a first (basic) check for the equivalence of two radiation spectra. Particular threshold values for count-rate differences could be based on the expected standard deviation of the data. Figure 4 shows an extreme example, in which the weapon-grade

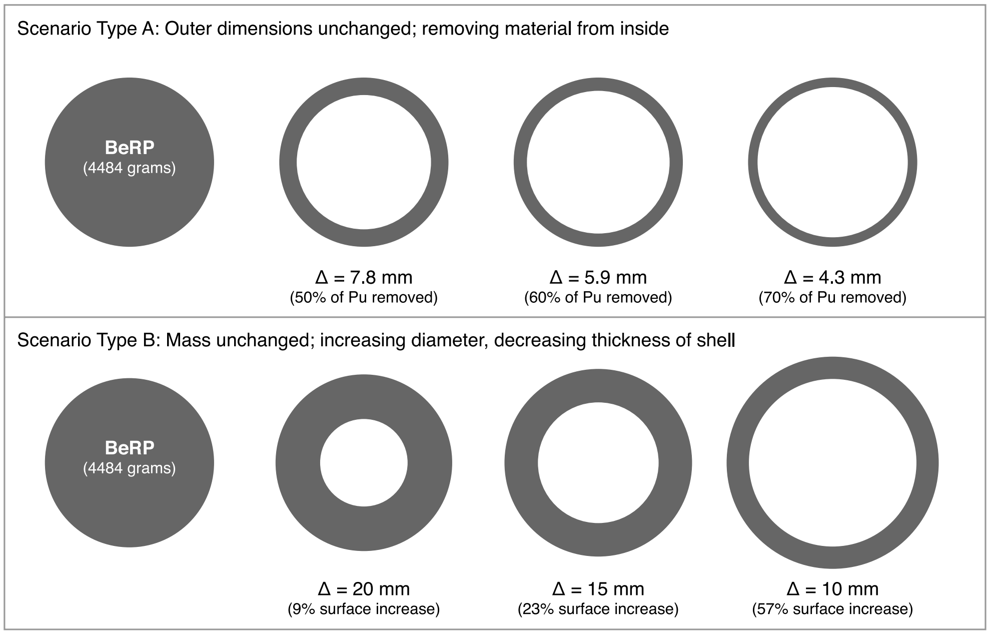

Figure 3: Scenario Types A and B. Series A is used to test the sensitivity of the inspection system to material diversions while the outer dimensions of the component remain unchanged. Series B is used to test the sensitivity of the system to changes in the geometry of the item while the mass of the item is kept constant. Both types are examined with simulated high-resolution (HPGe) and low-resolution (NaI) detectors.

plutonium in the BeRP ball is replaced with reactor-grade plutonium. In the 300–700-keV range, the observed count rate of the RPu ball is about 1.86 times higher than the rate of the original ball. Differences at this level are straightforward to detect and not studied any further below.

Spectral features: In order to compare two acquired data for spectral anomalies, we use the Kolmogorov-Smirnov test.[12] This standard statistical test first determines the (empirical) cumulative distribution functions (CDFs) of two spectra, i.e., the fraction of the counts observed as a function of the energy or channel number, and then uses the maximum distance between the two CDFs as a measure for their similarity. Based on this metric, the test provides probabilities that two data sets are drawn from the same probability distribution; here, it is used to decide if two gamma spectra originate from the same nuclear component. For the assessments below, we focus only on photons in the 300–700 keV range, so that the results are (more) robust against external shielding effects, which are not relevant here, but likely to be present in real-world situations.

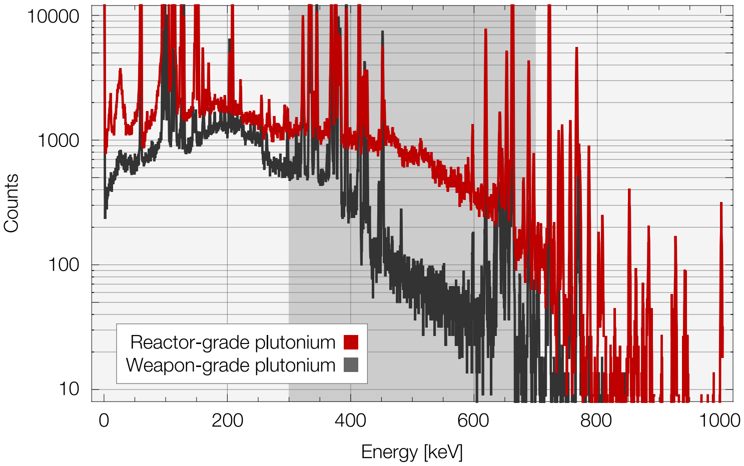

Figure 4: Simulated HPGe gamma spectra for the original (weapon-grade) BeRP ball and a similar ball made of reactor-grade plutonium (60.3% Pu-239; 24.3% Pu-240).

Scenario Type A

Scenario Type A examines the effect of removing material from the interior of the BeRP ball. Given the attenuation coefficients for gamma radiation in metallic plutonium, one cannot expect detectable difference in the spectrum for modifications far away from the surface of the ball, which has a radius of about 3.8 cm. For photons in the 600-keV range, $(\mu/\rho) \approx 0.14$ cm^2/g, which corresponds to an attenuation coefficient of about 2.7 cm^{-1} for metallic plutonium; in other words, only about $\exp(-2.7) \approx 7\%$ of all 600-keV photons will survive a thickness of one centimeter. The simulations confirm that the observed total count rates do not significantly change even if 70–80% [check] of the material is removed from the ball.

Spectral anomalies are more promising as a strategy to capture diversion scenarios of Type A. While difficult or impossible to distinguish "visually," the performance of the Kolmogorov-Smirnov test gradually improves as the thickness of the shell is reduced. Figure 5 summarizes the main results of a series of simulations for plutonium shells with thicknesses of up to 10 mm. The results show that passive gamma-ray spectrometry using the template-matching approach analyzing only the 300–700 keV range of the spectrum is able to detect diversions of Type A once the shell-thickness of the inspected plutonium item is less than 4–5 millimeters. Remarkably, the performance of the low-resolution NaI detector is not significantly inferior to the performance of the high-resolution HPGe detector. Overall, it should be possible to confirm the distinguish plutonium components similar to the present type if their thickness is on the order of 4 millimeters or less.

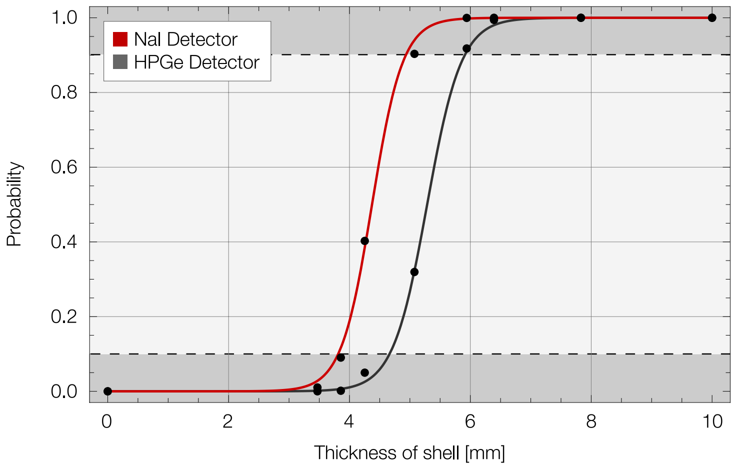

Figure 5: Results of the Kolmogorov-Smirnov test comparing the gamma radiation spectra in the 300–700-keV range from the solid BeRP ball with shells of the same outside diameter but with different thicknesses. Values indicate the probability that the two radiation spectra are considered equivalent or, mathematically, that the data sets are drawn from the same probability distribution. Once the shell thickness drops below 4 millimeters, the test can reliably distinguish the shell from the solid ball. Every data point is based on about 3,000 hours of single-CPU computer time; as shown, data points can be approximated by logistic functions.

Scenario Type B

Scenario Type B examines the effect of changes in the geometry of the item while the mass of the item is kept constant. Here, we start from the solid BeRP ball and gradually decrease the thickness of the shell (Figure 3). As in the previous case, spectral changes cannot be detected using statistical tests on the data in the 300–700-keV range if the thickness of the shell is larger than 4–5 millimeters. In contrast to the Type A scenarios, however, the observed total count rate now scales directly with the surface area of the component. For example, the shell with a thickness of 15 millimeters has a surface area that is about 23% greater than the surface area of the solid BeRP ball of the same mass. Similarly, the shell with a thickness of 10 millimeters has a surface area that is almost 60% greater. Respective count-rate increases would be readily detectable, and passive gamma-spectrometry therefore appears adequate to detect modifications that involve significant changes in the surface area of an inspected item containing special nuclear material.

Conclusion

Passive gamma spectrometry could be one of the basic measurement techniques to provide confidence in the authenticity of a nuclear warhead or a warhead component slated for dismantlement. When combined with an information barrier, it can be used with both attribute and template-matching approaches. Gamma spectrometry is generally not suited to determine the mass of fissile material in a massive nuclear component; for the same reason, it is therefore also not suited to confirm that two items are identical. There may be certain types of nuclear components, however, where passive gamma spectrometry may be deemed valuable and perhaps even sufficient as an inspection technique.

In this paper, using a series of computer simulations, we have examined the viability of a template-matching approach for a series of diversion scenarios starting with a solid ball of weapon-grade plutonium. The analysis is based on both differences in total count rates and statistically significant anomalies in the gamma spectra in the 300–700-keV range, where most of the prominent plutonium lines are located. Using simulated data, the results show that removal of material and isotopic changes are readily detectable once the thickness of plutonium shells is on the order of 4–5 millimeters or less even when these modifications are invisible from the outside. The performance of low-resolution (NaI) detectors is not significantly below the performance of high-resolution (HPGe) detectors for this application.

Complementary measurement techniques, for example using passive neutron detection or active neutron interrogation, could provide additional confidence in the authenticity of an inspected item. Moreover, there may be other regions of interest in typical gamma spectra (for example, in the high-energy range and signatures from (n, γ) reactions) that could be analyzed using some of the methods described here. It may be more challenging, however, for participants to identify relevant regions of interest in these gamma spectra (if they perceive this information sensitive) and to agree upon algorithms to compare them. Joint research in this area could begin with an agreement on unclassified "universal test objects" containing special nuclear material for further study and to define benchmark diversion scenarios for these objects.

Acknowledgements

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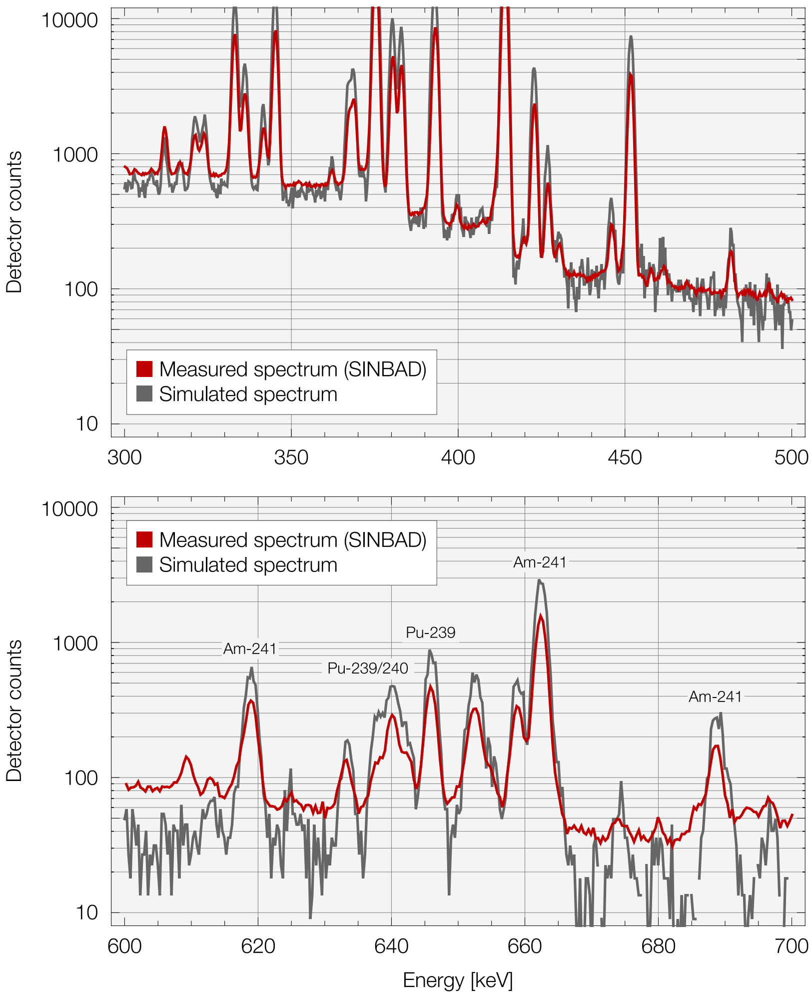

Figure 6: Measured and simulated high-resolution gamma spectra for the standard BeRP ball (weapon-grade plutonium with 0.25% Am-241). Some prominent plutonium lines are highlighted for the (600–700)-keV range; the lines in the (300–500)-keV range are all from Pu-239. Simulations are based on about 3,000 hours of single-CPU computer time.

Endnotes

[1] The United Kingdom–Norway Initiative: Further Research into the Verification of Nuclear Warhead Dismantlement, *NPT/CONF.2015/WP.31, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, United Nations, New York, 22 April 2015.*

[2] *K. M. Tolk et al., "Trusted Radiation Inspection System," 42nd Annual INMM Meeting, Indian Wells, CA, July 2001.*

[3] *Standard approach is neutron multiplicity counting. Diana G. Langner, "Measuring Plutonium Mass by Neutron Multiplicity Counting," p. 37 in David Spears (ed.),* Technology R&D for Arms Control, *U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Washington, DC, 2001.*

[4] *Dean J. Mitchell, "Minimum-Mass Estimates of Plutonium," pp. 38–39 in Spears, 2001,* op. cit.

[5] *As it names suggests, the BeRP ball was originally beryllium-reflected but is now primarily used with polyethylene reflectors of different thicknesses.*

[6] Shielding Integral Benchmark Archive and Database, Version December 2013, *SINBAD-2013.12, rsicc.ornl.gov/codes/dlc/dlc2/dlc-237.html and www.oecd-nea.org/science/wp/shielding/sinbad.*

[7] *John Mattingly,* Polyethylene-Reflected Plutonium Metal Sphere: Subcritical Neutron and Gamma Measurements, *SAND2009-5804, Revision 1, Sandia National Laboratory, Albuquerque, New Mexico, November 2009. See also John Mattingly and Dean J. Mitchell, "Implementation and Testing of a Multivariate Inverse radiation Transport Solver,"* Applied Radiation and Isotopes, *70, 2012, pp. 1136–1140.*

[8] *All decay radiation data are from: National Nuclear Data Center, Brookhaven National Laboratory, www.nndc.bnl.gov/nudat2.*

[9] *Spreading points on a disc and on a sphere, blog.marmakoide.org/?p=1; see also Helmut Vogel, "A Better Way to Construct the Sunflower Head,"* Mathematical Biosciences, *44 (3–4), June 1979, pp. 179–189.*

[10] *MCNP offers a special tally card for Gaussian energy broadening ("GEB"); by applying the broadening manually to the F8 tally data, several approximations can be tested and different detector types can be modeled with the same MCNP data saving significant amounts of computer time. Thanks to John Mattingly for this hint.*

[11] *The NaI detector used was a* Canberra *Model 802 scintillation detector connected to a* Canberra Osprey *digital MCA tube base.*

[12] NIST e-Handbook of Statistical Methods, *www.itl.nist.gov/div898/handbook (§1.3.5).*

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