

Low-resolution Gamma-ray Spectrometry for an Information Barrier Based on a Multi-criteria Template Approach

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Abstract

Gamma-ray spectrometry has been successfully employed to identify unique items containing special nuclear materials. Template information barriers have been developed in the past to confirm items as warheads by comparing their gamma signature to the signature of true warheads. Their development has, however, not been fully transparent, and they may not be sensitive to some relevant evasion scenarios. We develop a fully open template information barrier concept, based on low-resolution measurements, which, by design, reduces the extent of revealed sensitive information. The concept is based on three signatures of an item to be compared to a recorded template. The similarity of the spectrum is assessed by a modification of the Kolmogorov-Smirnov test to confirm the isotopic composition. The total gamma count rate must agree with the template as a measure of the projected surface of the object. In order to detect the diversion of fissile material from the interior of an item, a polyethylene mask is placed in front of the detector. Neutrons from spontaneous and induced fission events in the item produce 2.22 MeV gammas from (n, γ) reactions in the mask. This peak is detected and its intensity scales with the item's fissile mass. The analysis based on MCNP Monte Carlo simulations of various plutonium configurations suggests that this concept can distinguish a valid item from a variety of invalid ones. The concept intentionally avoids any assumptions about specific spectral features, such as looking for specific gamma peaks of specific isotopes, thereby facilitating a fully unclassified discussion. By making all aspects public and allowing interested participants to contribute to the development and benchmarking, we intend to maximize the concept's contribution to a more open and inclusive discourse on this matter.

Keywords: gamma-ray spectrometry, information barrier, template approach, nuclear warhead verification, nuclear disarmament, nuclear arms control, prompt-gamma activation analysis

1. Background

- 2 Current nuclear arms-control agreements between the United
- 3 States and Russia limit the number of deployed strategic nuclear

4 weapons each party can have. In the future, however, nuclear 33
5 arms-control agreements will most likely also place limits on 34
6 the number of nuclear weapons and warheads that a country 35
7 can maintain in its arsenal. Such agreements would require the 36
8 inspection and verification of warheads that are in storage and 37
9 queued for dismantlement. To accomplish this task, viable ver- 38
10 ification approaches must be available to confirm the authentic- 39
11 ity of nuclear components while also protecting classified in- 40
12 formation [1, 2]. One such approach would be to analyze the 41
13 gamma spectrum originating from an item identified for veri- 42
14 fication, and—through the use of an information barrier—only 43
15 confirm or deny the identity of the item as a valid nuclear com- 44
16 ponent without otherwise revealing any information about the 45
17 item. 46

18 Several information barriers have been developed based on 47
19 the attribute method, whereby a given set of attributes, such 48

20 as mass thresholds and isotopic ratios, are used to character-
21 ize these components. These systems typically require high- 49

22 resolution detectors, such as high-purity germanium detectors, 50
23 to perform this task. Since 2007, the United Kingdom and Nor- 51
24 way have been working on an initiative to develop and demon- 52
25 strate such an attribute measurement system [3]. A second ap- 53
26 proach, called template-matching, has been developed in par- 54
27 allel. The template approach does not seek to determine ab- 55
28 solute characteristics of the inspected item, such as plutonium 56
29 mass or isotopics. Instead, this complementary method seeks 57
30 to detect significant differences between two items, for exam- 58
31 ple by means of gamma spectroscopy, without seeking to de- 59
32 termine the origin for these differences. Despite the approach's 60

strengths, few such systems have been proposed and built [4];
among these, the Trusted Radiation Inspection System (TRIS)
developed at Sandia National Laboratories is the most promi-
nent and widely tested one [5]. While the general strategy of
TRIS has been described in the literature, not all relevant de-
tails of the developed algorithm are published.

In this paper, a concept for an open template approach is
proposed and evaluated based on its capability to detect the
most relevant evasion scenarios. One of them is the diversion
of fissile material. While passive gamma spectrometry is gener-
ally not well suited for determining the fissile mass in a nuclear
component due to self-shielding effects, we examine conditions
under which the technique is able to detect significant differ-
ences in the mass, in addition to isotopic composition and the
size of the item's surface, in simple configurations using simu-
lated gamma spectra.

2. Validation

Below, we will use extensive MCNP Monte Carlo simula-
tions to determine the expected performance of the inspection
system. In order to validate the models used for these simu-
lations, we draw on the high-quality SINBAD-2013.12 bench-
mark data for the so-called beryllium-reflected plutonium (BeRP)
ball. 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 (0.02 wt% Pu-238, 93.27 wt%
Pu-239, 5.91 wt% Pu-240, 0.07 wt% Pu-241, 0.03 wt% Pu-242)
enclosed in a thin steel casing. The ball was fabricated in 1980

and contained about 0.25 wt% of americium-241 at the measurement date (January 2009). The SINBAD exercise used a High-Purity Germanium (HPGe) detector for all gamma measurements [7, 8].

The simulated spectra are obtained using MCNP's pulse height tally. The following simulation procedure results in an accurate representation of the measured spectrum: First, a neutron simulation is run with a spontaneous fission source to determine induced fission rates as a function of the distance from the center of the BeRP ball. In a second simulation, induced fission reactions are not simulated during the neutron transport, but induced fission neutrons are directly included in the neutron source alongside spontaneous fission neutrons and the gamma rays from decay. In order to increase the efficiency of the Monte Carlo simulations, we place a large number of identical detectors on a spherical surface. Detectors can be evenly distributed on this surface using a modification of "Vogel's method" [9]. Particles that reach one of the detectors and leave it without interacting are terminated by the simulation to avoid the possibility of an unrealistic interaction in another detector. In order to further increase the simulation efficiency, we only include gamma energies above 100 keV because lower-energy gammas would be easily shielded and do not provide a robust signature for verification purposes. A typical run corresponding to a 60-minute measurement uses about 1000 hours of single-CPU computer time.

Figure 1 shows a comparison between the experimental data acquired during the exercise and the results obtained with MCNP computer simulations. In the measurement shown, the BeRP

ball was surrounded by a series of nesting spherical shells of high-density polyethylene, overall 3.0 inches thick. Neutrons are moderated and subsequently captured by hydrogen in these shells, resulting in the emission of high-energy gammas (2223 keV)—an effect that is further discussed below.

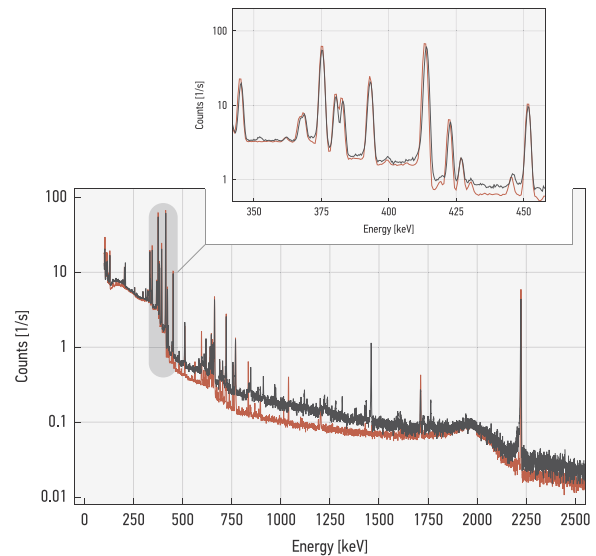


Figure 1: Measured and simulated high-resolution gamma spectra for the BeRP ball in a 3-inch polyethylene reflector. While the simulated background is slightly lower, the spectral features are well reproduced. Note the peak at 2223 keV, which is due to neutron capture in polyethylene.

3. Concept

In order to limit the amount of sensitive information acquired during a measurement, we examine whether robust results can be obtained with low-resolution detectors. While the information barrier concept prevents inspectors from accessing the spectral data, acquiring low-resolution spectra adds an additional layer of security. Similar to Sandia's TRIS, the proposed setup uses a sodium-iodide (NaI) detector with a 2-inch by 2-inch crystal (Figure 2). The detector resolution has been de-

104 terminated by measurements of various radioactive sources with
 105 the *Canberra* Model 802 NaI detector [10], and the respec-
 106 tive parameters are used for subsequent MCNP calculations to
 107 broaden gamma lines. A 15 cm thick polyethylene mask is
 108 placed between the source and the detector; this mask enables
 109 sensitivity to the neutron signature of the item via gamma de-
 110 tection from neutron capture in hydrogen. As the polyethylene
 111 also acts as gamma shielding, the mask has a central drilling
 112 to allow gammas to pass through without attenuation. A 5 cm
 113 thick steel plate (with a corresponding drilling) serves to atten-
 114 uate gammas that would otherwise scatter in the polyethylene
 115 and arrive in the detector, *inter alia* contributing to Compton
 116 background. The mask has an outer radius of 20 cm and a
 117 polyethylene mass of 17.6 kg. The detector is positioned 10 cm
 118 behind the plate. The mask's thickness and its distance to the
 119 detector are chosen based on MCNP simulations performed to
 120 identify a geometry to yield a sufficient 2223 keV peak inten-
 121 sity.

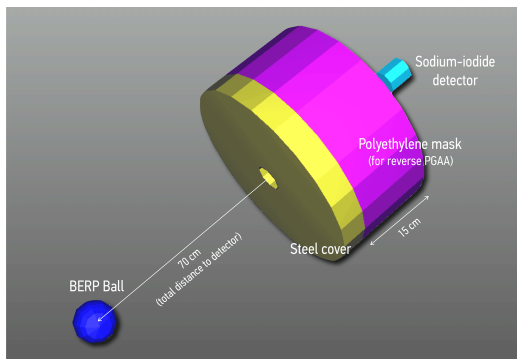


Figure 2: Simulated experimental setup for the multi-criteria template-
 matching approach.

122 Two principles guide the development of the system pro-
 123 posed here. First, we seek to avoid making assumptions about

the expected radiation signatures; in particular, we are not try-
 ing to tailor the algorithms to particular spectral features of ex-
 pected elements and nuclides such as uranium and plutonium.
 Candidate algorithms should be simple, versatile, and robust.
 Such an approach may also be easier to use and optimize in an
 unclassified setting. Second, we extend the standard template
 approach, which relies on a comparison of gamma spectra, by
 including two additional criteria in order to be more sensitive
 to important diversion scenarios that may otherwise be missed.
 Combined, the current criteria are:

Spectral features. The level of similarity between the ac-
 quired gamma spectrum and the template is determined by an
 “empirical” Kolmogorov-Smirnov (KS) test. In statistics, the
 standard two-sample KS test is a nonparametric hypothesis test
 that measures the similarity of two distributions. To do this, the
 test uses the largest absolute difference (D_{KS}) between the two
 cumulative distribution functions of the datasets as a measure
 of disagreement (Figure 3). It accepts the hypothesis that the
 distributions are equal if D_{KS} is less than a threshold value D_T ,
 which is determined by choosing a significance level [11, 12].
 The method has been previously and successfully applied to
 compare gamma spectra [13]. However, the original KS test
 will fail (i.e., reject the hypothesis that two measured spectra
 originate from the same source), if the measurement configura-
 tion, the detector voltage, or other experimental conditions vary
 to a very small extent. To account for such inevitable variations,
 we introduce the modified test, which interprets gamma spectra
 as probability distributions; we then empirically determine the
 D_T for a series of measurements on the same items to meet a

153 specified false positive rate.

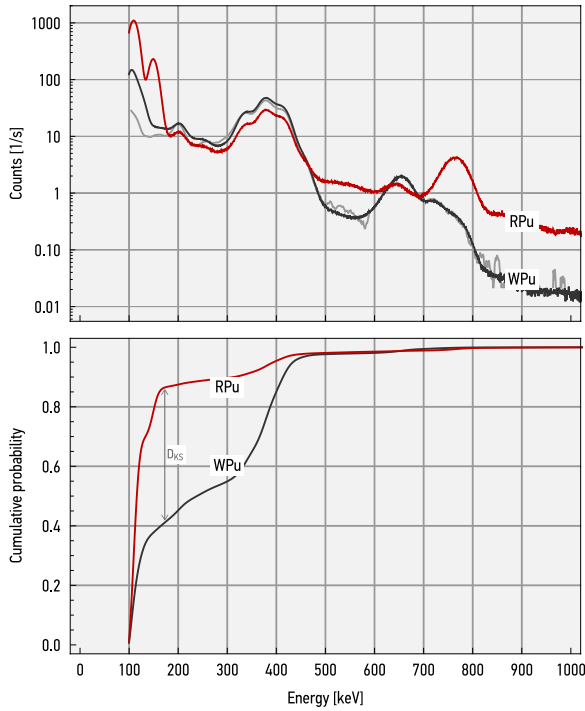


Figure 3: Quantifying the differences between two radiation spectra. Simulated gamma spectra measured of the original BeRP ball compared against the spectrum of a similar ball made of reactor-grade plutonium (top). The cumulative distribution function is equivalent to the fraction of the counts that have already been observed as a function of energy.

154 **Total gamma count rate.** The features of a gamma spec-
 155 trum are largely determined by the isotopics of the source and
 156 only weakly depend on the size of the object. In order to be
 157 directly sensitive to size, we therefore also compare the total
 158 gamma count rates observed for the template and the inspected
 159 item. To first order, these count rates scale with the projected
 160 surface area of the items (as seen by the detector) and provide
 161 a useful indicator for the similarity of their shapes.

162 **Total neutron count rate.** The gamma signature of mas-
 163 sive objects, i.e., objects with thicknesses that exceed several

164 millimeters, is dominated by the isotopics near the surface. The
 165 signature is much less sensitive to the presence of radioactive
 166 material away from the surface. For this reason, simple gamma
 167 measurements cannot be used for estimating the mass of an in-
 168 spected item; at best, they can provide a minimum-mass esti-
 169 mate [14, p. 38–39]. Most diversion scenarios involve remov-
 170 ing fissile material from an item, and an indicator that scales
 171 with mass would therefore be highly valuable. Here, we use
 172 neutron emissions from the item for this purpose. This works
 173 particularly well for plutonium components, but could also be
 174 adapted for uranium components when combined with a small
 175 “driver source.” In order to keep the inspection system as sim-
 176 ple as possible, one measurement using a single type of detec-
 177 tor is preferable. To do this, we use Prompt Gamma Activation
 178 Analysis (PGAA) [15] in reverse and place the polyethylene
 179 mask shown in Figure 2 between the source and the detector.
 180 This mask thermalizes neutrons emanating from the inspected
 181 item and converts them into high-energy gammas (2223 keV)
 182 following neutron capture in hydrogen [16]. The strength of
 183 this gamma line will be used as an indicator scaling with the
 184 mass of the object (Figure 4). If neutron multiplication in the
 185 inspected item is significant, then the dependency can be non-
 186 linear. Since, for the template approach, we only compare the
 187 equivalence of radiation signatures and are not interested in ab-
 188 solute mass measurements, understanding the functional rela-
 189 tionship is not necessary.

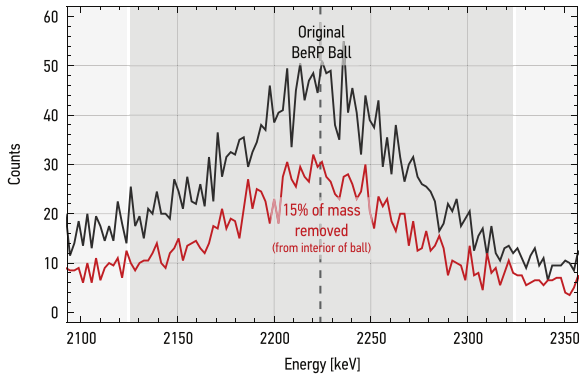


Figure 4: Gamma peak at 2223 keV following neutron absorption in hydrogen. Shown are the detector counts for the solid BeRP ball and for a hollow ball from which 15% of the material has been removed (3830 grams vs 4484 grams). The relative peak area drops by about 40% due to reduced mass and lower neutron multiplication in the hollow item. Shown absolute counts are for simulated 30-minute measurements.

4. Results

To evaluate the viability of the proposed method, we examine a series of diversion scenarios from the (bare) BeRP ball. These include scenarios in which the isotopics and the apparent size of the object don't match the values of the reference item. More importantly, we also examine the sensitivity of the inspection system to material diversions while the outer dimensions of the component remain unchanged (Figure 5). To achieve this, in the simulations, material is gradually removed from the interior of the BeRP ball, which would be difficult to detect with standard gamma spectrometry.

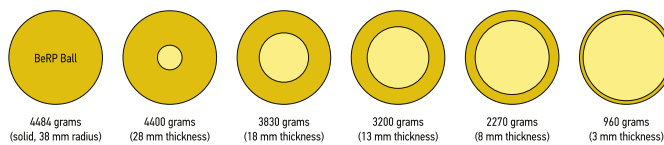


Figure 5: Diversion scenarios for the BeRP ball.

Spectral features are the primary indicator for the comparison of the radiation spectra acquired for the inspected item and the template. Figure 6 shows the “empirical” KS test results of a number of simulated five-minute measurements. With sufficient data, the false-positive rate can be adjusted to any desired value. In the present case, the maximum distance between the cumulative distribution functions obtained for measurements on the BeRP ball is well below $D_{KS} = 0.002$. Also shown are the results for a diversion scenario, where the Pu-240 content (relative to the Pu-239 content) is increased by 5%. Even for this rather small isotopic change, the KS-test returns significantly higher D_{KS} values with a mean of about 0.017; these values are easily distinguished from the valid case.¹ In practice, due to experimental conditions, the measured values and their variances can be expected to be somewhat larger than these simulated ones, but true values for matching items can be empirically determined and reduced, in particular, by increasing the allotted measurement time.

Total gamma counts are used as the second criterion, and Figure 7 summarizes the main results. The total counts are largely determined by two factors, the projected surface area (seen by the detector) as anticipated, and the isotopic composition of the item near the surface. Figure 7 shows results for an item that has the same mass as the original BeRP ball, but a larger outer diameter and for a 5% change in Pu-240 content. Even small differences in these features are easily detected. Accordingly, the same total counts could be obtained by

¹For more drastic changes in the isotopics, as shown for example in Figure 3, the observed D_{KS} values will be much larger.

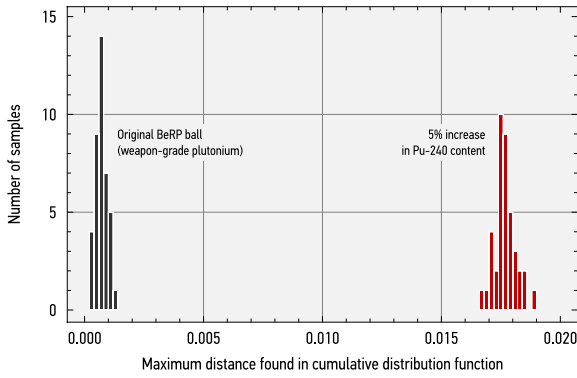


Figure 6: Empirical KS-Test for spectral features. Shown are results for 50 simulated five-minute measurements.

simultaneously changing both surface and isotopics. Changed isotopics would, however, be detected by the “modified” KS test. In contrast, total gamma counts are not particularly sensitive to the interior of the item. As shown in Figure 7, the total count decreases marginally even for scenarios, where on the order of 50% of the BeRP ball’s mass have been removed. Only when the thickness of the shell drops below 5–7 millimeters, the decrease becomes more significant. To be sensitive to the scenarios shown in Figure 5, an extra indicator is needed.

Neutrons emitted from the item are converted to high-energy (2223 keV) gammas via neutron capture in hydrogen. As illustrated in Figure 4, we use a 200-keV region-of-interest centered around this peak and use the total number of counts in that region as our third indicator. Figure 8 summarizes the results. As expected, items that have the same mass but different sizes are difficult to distinguish based on their neutron signature. Figure 8 shows that this indicator is sensitive both to mass differences between two plutonium components and changes in the Pu-240 isotopics, as spontaneous fission neutrons, which induce fur-

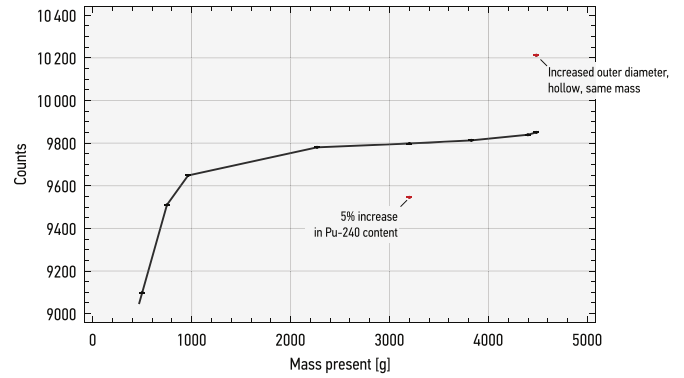


Figure 7: Total gamma counts per second as function of the mass present. Using the total count rate, it is difficult to distinguish the solid BeRP ball from a shell as long as the thickness of the shell exceeds 10 mm. The total count rate is most sensitive to projected surface area (geometry changes) and isotopics. Shown error bars are for simulated 30-minute measurements.

ther fission events in the item, primarily come from Pu-240. Accordingly, the same peak counts could be obtained by simultaneously changing both fissile mass and isotopics. As changed isotopics would, however, be detected by the “modified” KS test, the proposed method is able to reject items with material withdrawn from the interior.²

5. Discussion and Outlook

In this article, we propose a measurement approach to support treaty verification applications based on low-resolution gamma-spectrometry for use in a template-matching information barrier. The goal is to increase the robustness against evasion attempts compared to previously built systems. In particular, we

²An adversary could colocate a concealed neutron source with inspected item in an attempt to reproduce the total neutron count rate observed for the reference item; this strategy would, however, run the risk of generating additional detectable signatures; for example, a neutron source could affect features of the gamma spectrum.

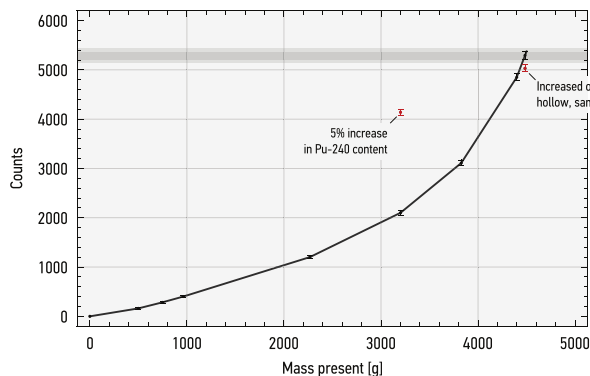


Figure 8: Total neutron counts as a function of the mass present. The nonlinearity is due to the increasing neutron multiplication as the mass of the item increases, i.e., as the size of the cavity in the item decreases. 4484 grams corresponds to the solid BeRB ball. Also shown are two additional diversion scenarios. Shown absolute counts are for simulated 30-minute measurements.

propose the use of multi-criteria templates to simultaneously detect changes in isotopics, mass, and size or shape. As summarized in Figure 9, each indicator can be optimized for one particular attribute, but it will often also be sensitive to other relevant characteristics of the inspected item, making cheating particularly difficult. As one specific implementation of the proposed concept, our analysis shows that the combination of an empirical Kolmogorov Smirnov test, the total gamma count rate test, and the total neutron count rate test (combined with a polyethylene mask) constitute an effective concept to distinguish valid from invalid plutonium items.

As a next step, experimental testing with special nuclear materials, with both high and low neutron emission rates (plutonium and uranium), would help provide a nuanced understanding of systematic uncertainties from factors that typically cannot be taken into account in the simulations, as for example noise from the experimental equipment or small variations in

the placement of the inspected item and the detector.

Our information barrier concept intentionally avoids the necessity of assumptions about specific spectral features, such as looking for gamma peaks of specific isotopes. This approach is followed in order to facilitate a fully unclassified discussion, which we believe is necessary for the successful implementation of a multinational verification regime. Furthermore, openness and transparency are essential principles to optimize the robustness of information barriers, as it enables cooperative research. This principle has never before been applied to template information barrier research. Ours would be the first open and transparent template information barrier design. Interested participants will then have the possibility to peer review and improve the algorithms or use their own algorithms for benchmarking purposes, contributing to an inclusive scientific discourse on this matter.

	MODIFIED KS TEST	TOTAL GAMMA	TOTAL NEUTRONS
ISOTOPICS	Excellent indicator (in combination with others)	Good indicator (in combination with others)	Good indicator (in combination with others)
SIZE (PROJECTED SURFACE)	Good indicator (in combination with others)	Excellent indicator (in combination with others)	Inadequate
MASS	Weak indicator	Weak indicator	Excellent indicator (in combination with others)

Figure 9: Summary of the capabilities of our proposed system to detect different isotopic compositions, projected surfaces and fissile masses.

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