Backscatter Surrogate for Highly Enriched Uranium

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INTRODUCTION

Currently, the United States faces a great challenge in increasing its readiness in the event of a criminal act involving radiological material. In a 2009 speech delivered in Prague, President Barack Obama highlighted the importance of nuclear security in the world today by proclaiming that nuclear terrorism "is the most immediate and extreme threat to global security"[1]. While the acquisition of Plutonium (Pu) may be easier than that of Highly Enriched Uranium (HEU), the fabrication of a plutonium weapon is likely to be harder than a Uranium weapon due to spontaneous fission. The construction of a Uranium (U) based weapon in the gun-type assembly is regarded as feasible and there is evidence that the A. Q. Kahn (Pakistan) design that has proliferated is a HEU based gun type device[2]. In addition to the threat of improvised nuclear weapons, the use of radiological material in concurrence with any type of conventional weapon ("dirty bomb") is still credible[3]. As such, it is very important that the United States continually improve its capability to detect the transport and presence of radiological material out of regulatory control.

An imperative exists for the creation of a viable and affordable HEU surrogate. DTRA has shown strong interest in the development of better Special Nuclear Material (SNM) sources for training[4]. A currently used surrogate gamma ray source for HEU without any HEU is ^{57}Co[5]. ^{57}Co is problematic as a surrogate for HEU; it has a short half-life of 271 days, emits gamma rays well below the energy of those emitted by ^{235}U, and emit none at the higher energies associated with ^{238}U[6]. Alternatively, there are HEU surrogates that use amount of ^{235}U significantly smaller than would be seen in a weapon core. While these pit-style surrogates boast an extremely high-fidelity match to the gamma signature of HEU, they cost nearly $500,000 per unit and are also difficult to handle and move as they still contain a sizeable amount of SNM. This project seeks to use a novel approach that takes advantage of the backscatter phenomenon seen in gamma ray spectroscopy to design, model, construct, and test a prototype HEU surrogate source that would be inexpensive, easy to construct, and yet match the actual HEU signature with high fidelity.

Background

Fissile isotopes of U and Pu, the materials of highest priority for detection, are classified as SNM. Upon decay, SNM emits detectable radiation in the form of gamma rays (U and Pu) or neutrons (Pu only). Gamma ray emissions occur at known energies, and a unique gamma ray emission spectrum can be observed for specific isotopes[7]. These spectra can be thought of as the "fingerprints" for SNM and other radiological material. HEU comprises the fissile isotopes ^{235}U and ^{238}U, with greater than 90% of the isotopic composition being ^{235}U. It has a gamma signature that includes photons from ^{238}U daughter product decay and from ^{235}U decay. As seen in Figure 1[8], the primary peak of the HEU gamma signature occurs at the relatively low energy of 186 keV, while the peaks associated with the decay of ^{234m}Pa, a 238U daughter product, are visible at 743, 766, 786, and 1001 keV.

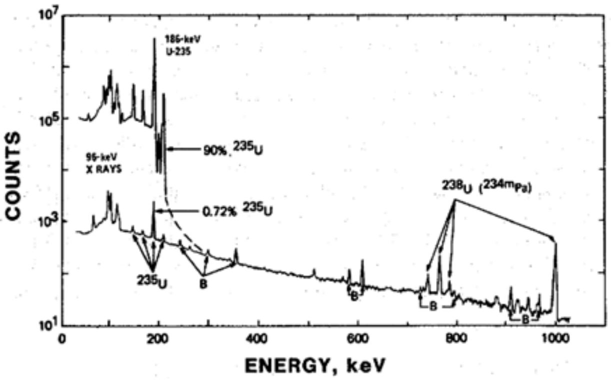

Fig 1. Gamma Signature of HEU with 186 keV ^{235}U peaks as well as the 743, 766, 786, and 1001 keV peaks from ^{238}U.

In order to optimize the effectiveness of both detection systems and protocols, testing is essential. To test detection capabilities, surrogate materials that mimic the radiological signatures of SNM are used in order to avoid the difficulty and cost associated with the use of actual nuclear material.

The proposed surrogate takes advantage of a phenomenon seen in gamma rays known as Backscatter. Backscatter generally refers to a process in which gamma rays first interact via Compton scattering with a high scattering angle and then continue at reduced energy. Gamma rays scattered directly backward, or "backscattered", create an observable peak at the energy described by Equation 1[9],

$$E_{Backscatter} = \frac{E_{emitted}}{1+\frac{2E_{emitted}}{m_0c^2}} \tag{1}$$

Where m_0c^2 is the electron rest energy of 511 keV. The β^- decay of ^{137}Cs to metastable ^{137}Ba and then to stable ^{137}Ba releases 662 keV gamma rays. Equation 1 predicts a backscatter peak for ^{137}Cs at 184 keV, which is very close to the 186 keV peak seen in HEU. Therefore, ^{137}Cs is a promising candidate radioisotope for use in creating an HEU backscatter-based surrogate. Additionally, the frequency of backscatter is an important consideration. The Klein-Nishina formula predicts the angular distribution of scattered gamma rays according to the relationship described by Equation 2[10].

$$\frac{d\sigma}{d\Omega} = Z{r_0}^2 ABC \tag{2}$$

$$A = \left(\frac{1}{1+\alpha(1-\cos(\theta))}\right)^2 \tag{2a}$$

$$B = \frac{1+cos^2(\theta)}{2} \tag{2b}$$

$$C = 1 + \frac{\alpha^2(1-\cos(\theta))^2}{(1+cos^2(\theta))(1+\alpha(1-\cos(\theta)))} \tag{2c}$$

Where Z corresponds to atomic number of the scattering material, r_0 is the classical electron radius, and α is defined as E/m_0c^2. An integration of this expression from 2.61799 radians to 3.66519 radians (an arc of 60° centered on π radians) yields a cross-section for scattering at between those angles. The ratio between the 60° cross-section and that found by integrating from 0 to 2π is 0.076393, indicating that 7.64% of the gamma rays that scatter will do so at an angle between 150° and 210°. This indicates that either an efficient design or a strong ^{137}Cs source is required for a viable surrogate.

In detecting gamma radiation, a common technique for real-time detection is the use of scintillation, in which a crystal luminesces upon contact with ionizing radiation and the light emitted is detected. A common detector type used in field detection and characterization is the Sodium-Iodide (NaI) scintillation detector. Such detectors tend to be more portable and less expensive, but lack energy resolution. This resolution can be quantified in the form a Full-Width-At-Half-Maximum (FWHM), in which a smaller FWHM indicates a sharper photopeak and better resolution. As an example, a sensor with 7% resolution will have a FWHM value of 13 keV at a mean energy of 186 keV.

Note that within a 30 degree backscatter half-cone angle, the backscattered photons will range in energy from 184 keV to 188 keV, a range considered indistinguishable on a NaI detector. An alternative to scintillators are semiconductor radiation detectors, which offer increased resolution, but at higher cost and lower portability. Figure 2[11] offers a comparison between two photopeaks for the same source, one produced with a NaI scintillator and one produced with a High-Purity Germanium (HpGe) semiconductor detector.

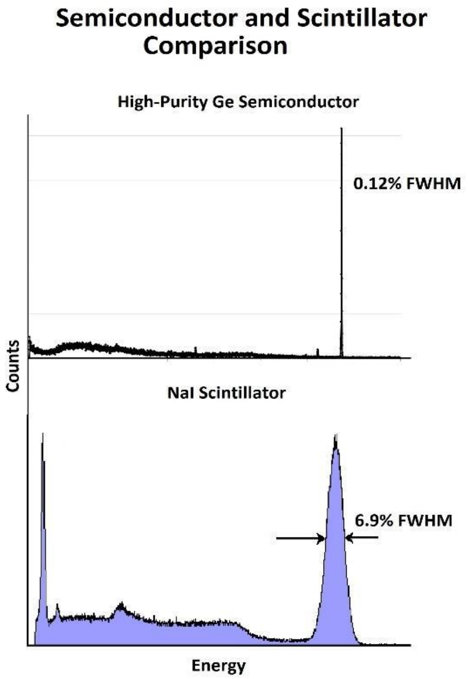

Fig 2. Comparison between Semiconductor and Scintillation Detector Resolution

As can be seen, semiconductor detectors tend to have significantly better energy resolution. As a result, it was decided that for this research, a high-purity Ge detector would be used for gamma spectroscopy during surrogate testing and development, while the end use of the source is intended for scintillation systems. While use of a scintillator may make it easier to replicate the signature of HEU, the precision of a semiconductor can better characterize the fidelity of the match between real HEU and the surrogate produced.

Methodology

The immediate design challenges prevalent in creating a backscatter surrogate are the viability of using backscatter to create photopeaks as well as an issue of geometry in creating a source that shields direct gammas but allows those that are backscattered to proceed. It was preferred that modeling be used to assess complex geometries before fabrication.

With the challenges to design in mind, a three-phase methodology was employed to most efficiently and accurately attain the desired surrogate; statistical model and concept validation, modeling and geometrical optimization, fabrication and testing. Phase 1 refers to the process of experimentally validating the concept of backscatter as a viable mechanism for creating gamma signature surrogates. As well, it is important to validate the modeling software MCNP6® as accurate in situations involving scattered photons. Once the backscatter concept and the MCNP® model were shown to be viable, phase 2 commenced, seeking to model both simple and complex geometries designed to maximize source strength and the sharpness of the 184 keV peak observed. The third and final phase is then building the optimal geometry specified by phase 2 and experimentally testing that source against a high-fidelity pit-style surrogate.

Results and Analysis

Phase 1

Phase 1 designed an experiment in which a shielded 10 μCi ^{137}Cs source sent gamma rays toward a wall, allowing them to backscatter toward a detector on the other side of the shield. Figure 3 illustrates the experimental setup. The shielding materials used were individual 5.08 x 10.16 x 20.32 cm lead bricks.

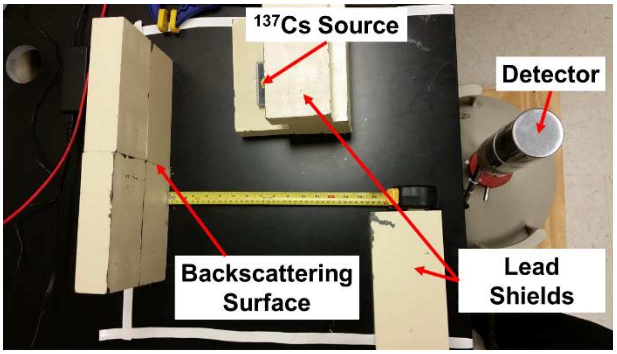

Fig. 3. Experimental Layout

The detector used in this experiment was a liquid nitrogen cooled Canberra® GC4018 model high-purity Ge detector. The detector uses a Ge crystal with a diameter of 62.00mm and a length of 60.30mm. Gamma-ray data were recorded, analyzed, and plotted.

The experimental setup illustrated in Figure 3 is the geometry used in a day-long collection to satisfy the objective of phase 1. Two different radiation collections were taken that each lasted 24 hours: One with the source and one without the source to characterize the test area's radiation background. The resulting corrected spectrum is pictured in Figure 4. The spectrum had, as expected, a very large peak at 184 keV and only a small amount of 662 keV photons. The sharpness of the 184 keV peak was visibly less than a traditional photopeak. However, the prevalence of the peak was enough to verify the feasibility of using backscatter for creating a surrogate.

The experimental setup was then modeled in MCNP6®. The model included the table, lead bricks, air workspace, and high-purity Ge detector. An energy pulse tally (F8) with a Gaussian Energy Broadening (GEB) term was used to simulate the Ge detector. The GEB term used parameters calculated to match the provided design specifications of the Canberra detector[11]. The results of the MCNP6® simulation are summarized and compared with the results of the experiment in Figure 4, indicating that the objectives of phase 1 were successfully met.

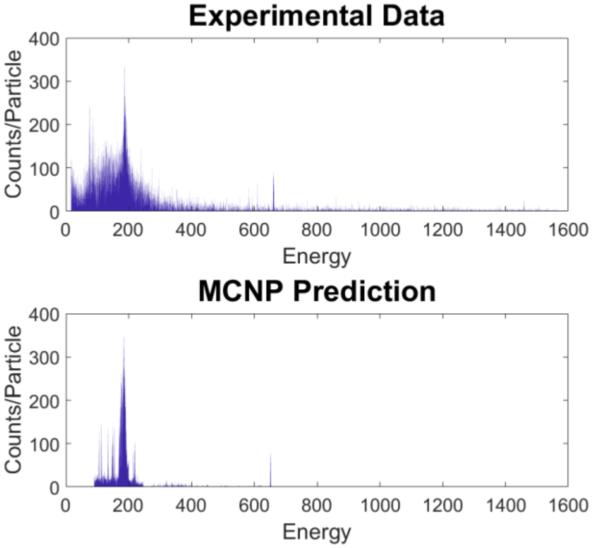

Fig. 4. MCNP compared to Experimental Data

Phase 2

Two representative notional designs were used in preliminary optimization simulations. The notional design concepts were the "soccer ball" and the "lantern". Each design consisted of a spatial iteration of a more basic building-block. The building blocks, as well as the notional design concept of each candidate design are illustrated in Figure 5.

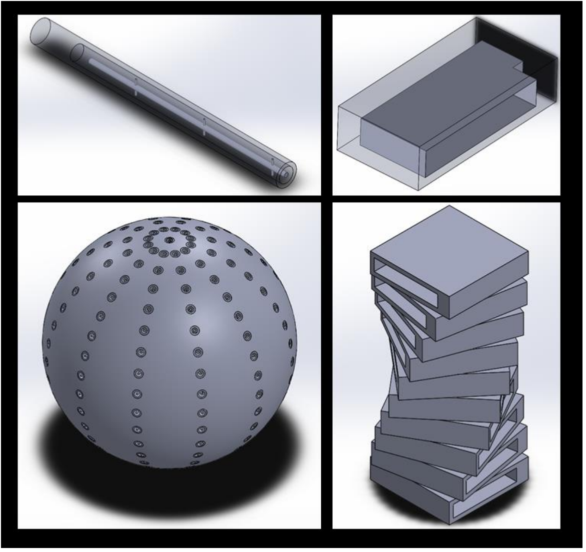

Fig. 5. Building Block for Soccer Ball (Top Left), Soccer Ball (Bottom Left), Building Block for Lantern (Top Right), and Lantern (Bottom Right)

The soccer ball design used a collimator-style building block that was to be placed in a lead ball. The source rests behind a thin, long shield designed to prevent 662 keV primary gammas from making it to the detector un-scattered. Gammas rays that first scatter off of the lead base portion of the assembly and then proceed to the detector after having scattered at an angle of ~180°. The lantern design uses boxcar-style building blocks that stack on top of each other at a radial pattern. As illustrated, the source rests behind a lead shield to one side of the box, forcing the primary ^{137}Cs gammas to scatter off of a back side before approaching a detector.

Building block designs were optimized through modelling. With regard to the collimator building block, the optimum shield to area ratio was found to be ~50%. For the lantern's building block, the angle at which the scattering surface recesses was optimized at 30°.

The optimized designs were assessed through modelling and simulations on the bases of photopeak resolution, efficiency, spatial fidelity, and cost. Photopeak resolution was considered a measure of the sharpness of the 184-keV peak predicted by MCNP6® and is indicated by FWHM. Efficiency was considered to be the ratio between the number of gammas emitted by a ^{137}Cs source and the number that ultimately reached the detector. Spatial fidelity was considered the rate of change in the overall spectrum as a function of detector position relative to the surrogate. Prices of production were estimated based on the volumes of shielding materials required, sources, and machining costs. A summary of the assessment results can be found in Table I.

TABLE I. Design Assessment

Design Metric	Soccer Ball	Lantern
Photopeak Resolution FWHM	9 ± 1 keV	2 ± 1 keV
Efficiency (average)	>1%	3.2%
Spatial Fidelity	360 deg^2	360°
Price of Production (est.)	\$15,000	\$8,000

To determine the highest performing design, a weighted decision matrix will be employed in which each evaluation criterion is assigned a weight indicative of its performance. Weighted scores in each metric will then be summed and used to determine the best design.

Phase 3

Phase 3 will build and test the design selected by phase 2. Comparisons will be made to the MCNP model prediction from phase 2 as well as to a characterized HEU pit-style surrogate available to the United States Naval Academy. The characterized spectrum for the SNM based surrogate is shown in Figure 6. It is important to note that while this project focuses on replicating the 186 keV peak of ^{235}U, the overall gamma ray spectrum for HEU includes higher-energy x-rays from ^{238}U decay. The final surrogate would thus be supplemented by a source of natural U, which is more available and more easily handled than HEU, providing a broad spectral match of the SNM.

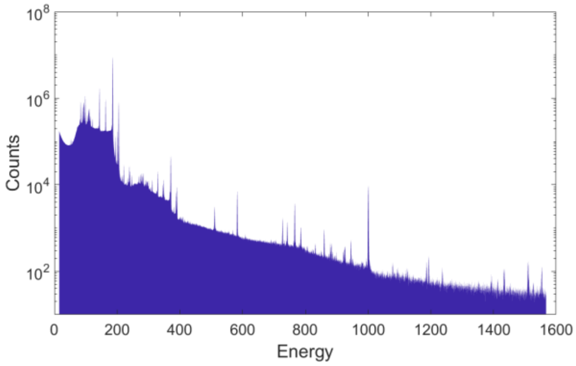

Fig. 6. HEU Surrogate Characterization

Conclusion

High fidelity, inexpensive, and easy to handle surrogate materials for SNM are of paramount importance to national security. A method for creating such a surrogate takes advantage of the backscatter of gamma rays from ^{137}Cs. This research investigated the potential for such a surrogate, and built and tested a candidate surrogate. As of this submission, the three-phase project has successfully completed validating the concept of a backscatter-based surrogate as well as the use of MCNP6® to model backscatter in complex geometries. The second phase has begun, complex design modeling and selection, and will complete by the end of 2017. Construction and experimental verification will then be completed by February 2018.

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