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Radioisotope Discrimination Algorithm for Arms Control Inspections

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Abstract

Potential future arms control treaties may include warhead verification measurement scenarios which could require the use of intrusive inspection technologies such as spectroscopic gamma radiation measurement and neutron counting. These technologies, although highly capable of confirming the presence or absence of nuclear warheads, pose serious information security risks. Sandia National Laboratories has continued to develop a technique to confirm the presence of weapons usable nuclear material without collecting or storing a gamma radiation spectrum. By individually weighting each measured pulse in list mode, a scalar value is used to confirm the expected radioisotopic composition of the item being measured. This method can help deliver an option for a more easily trusted attribute measurement system in future arms control treaties.

Introduction

As an introduction to the basic approach of the Unclassified Radioisotope Algorithm, the following section from a previous publication[1] is presented:

To determine if the object being measured is consistent with a warhead or warhead component, the measured spectra is compared against undesirable radioisotopes that could be substituted. This is done by constructing an importance weighted matrix and binning each individual photon count in list mode. This rolling calculation ensures that a spectrum is never collected.

For the notional spectrum in Figure 1, the weighting array element is set to 0 where the two spectra are close to the same value. The element is set to 1 where the desired spectrum has a peak or feature in absence of a corresponding peak of the undesired spectrum. The element is set to -1 where the reverse is true. If both spectra have a correlated peak, the element is again set to 0.

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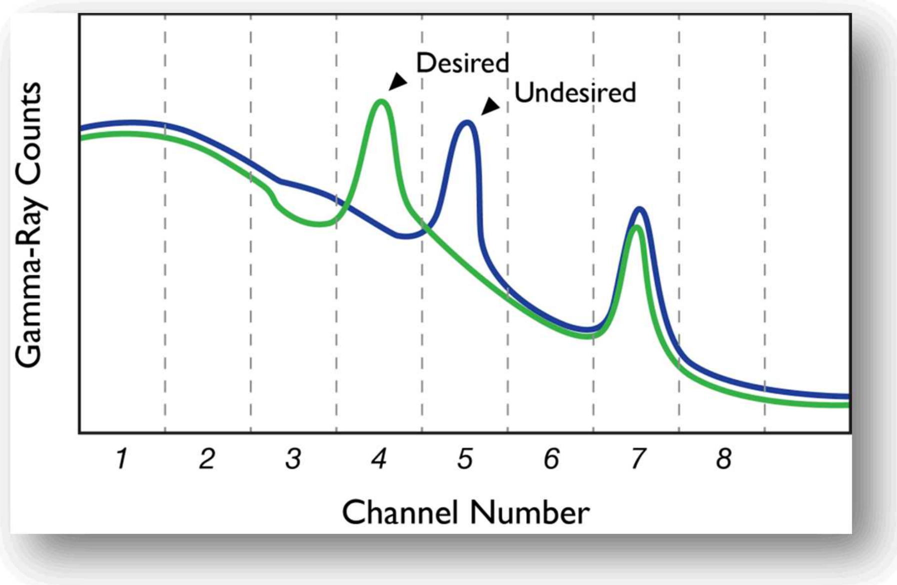

Figure 1 - Notional Spectra

Utilizing this technique as a running calculation, the resultant will trend positive for spectra corresponding with the desired spectrum and negative for spectra corresponding to the undesired spectra. The process will continue until a sufficient number (N_{max}) of gamma-rays have been collected to allow the desired statistical certainty to be reached.

Results

Initial algorithm testing used simulated high purity germanium (HPGe) spectra generated by Gamma Detector Response and Analysis Software (GADRAS)[2] to prove the feasibility of this concept. Continued algorithm development leveraged NaI detector models to explore the performance of applying the algorithm to medium resolution gamma detectors. The result of this study was that medium resolution detectors such as NaI produced performance very comparable to the ultra high resolution HPGe results for a range of different plutonium and uranium sources.

Figure 2 illustrates simulated spectra (with approximately 1,000,000 counts total for each source) generated for an HPGe detector measuring weapons grade plutonium (WGPu) and reactor grade plutonium (RGPu). The many closely spaced photopeaks convey the potential difficulty in discriminating WGPu from RGPu.

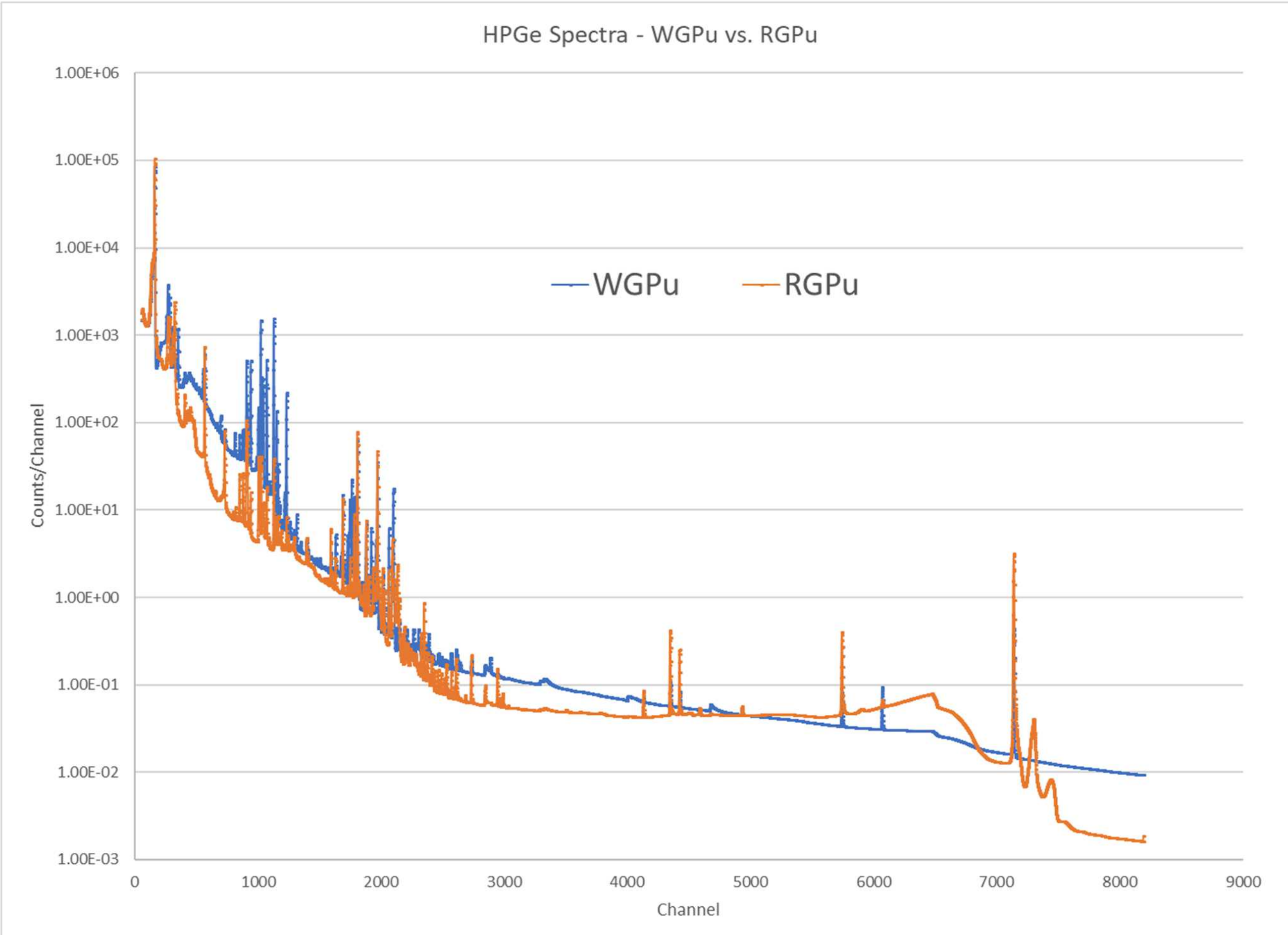

Figure 2 – WGPu and RGPu HPGe Spectra

In addition to directly comparing the performance of NaI and HPGe detectors, the effect of varying thresholds for weighting array values is explored. In one case, weighting arrays were automatically generated by comparing desired and undesired count rates for each channel in a pair of simulated spectra (desired and undesired), assigning either +1 or -1 values if the expected counts in each bin differed by one sigma (in this case, defined as the square root of the average counts). The performance of the algorithm is then compared against setting a five sigma threshold for weight values.

Figures 3 and 4 below illustrate the respective performance (algorithm scalar value) of a NaI and HPGe detectors in discriminating WGPu and RGPu, for both one and five sigma threshold settings.

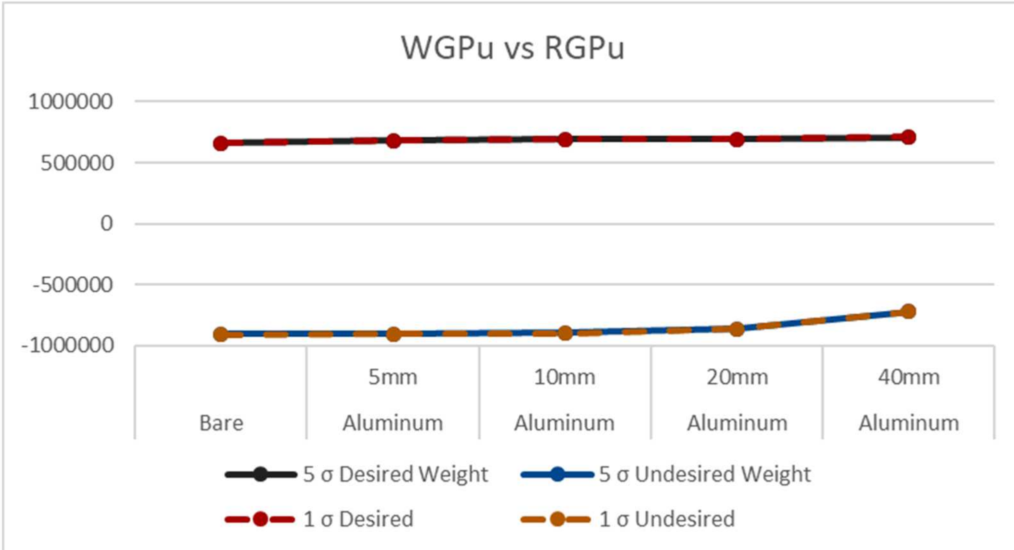

Figure 3 – NaI Detector Scalar Values: WGPu versus RGPu

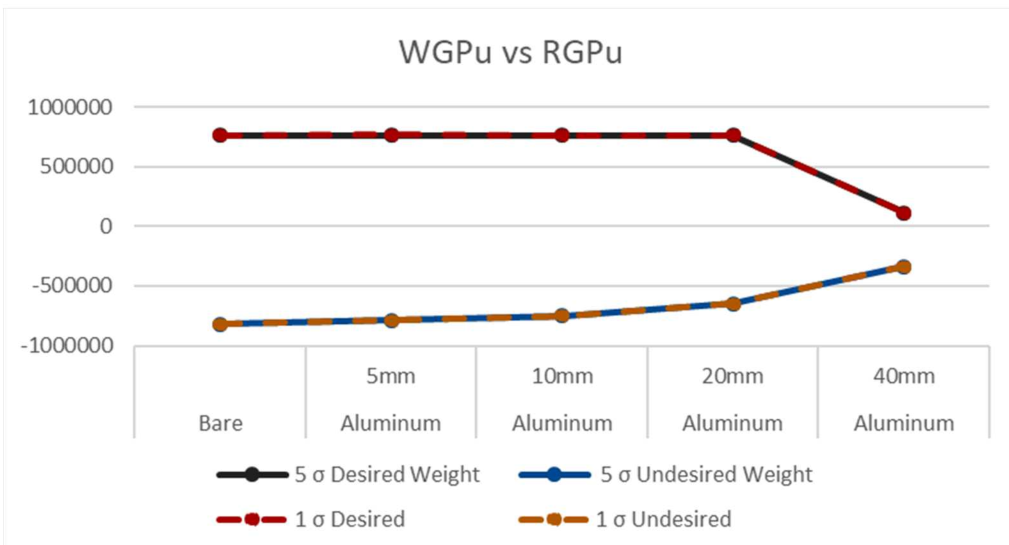

Figure 4 – HPGe Detector Scalar Values: WGPu versus RGPu

As show in Figures 3 and 4, there is virtually no difference in increasing the weighting array thresholds from one to five sigma, for WGPu and RGPu. This behavior is consistent for all sources modeled thus far, indicating that the spectra are sufficiently unique for the energy range of interest. Surprisingly, the medium resolution NaI detector appears to outperform HPGe in terms of scalar value discrimination across a range of shielding configurations.

Figures 5 and 6 display the medium resolution WGPu and RGPu spectra across a range of shielding configurations compared in Figure 3.

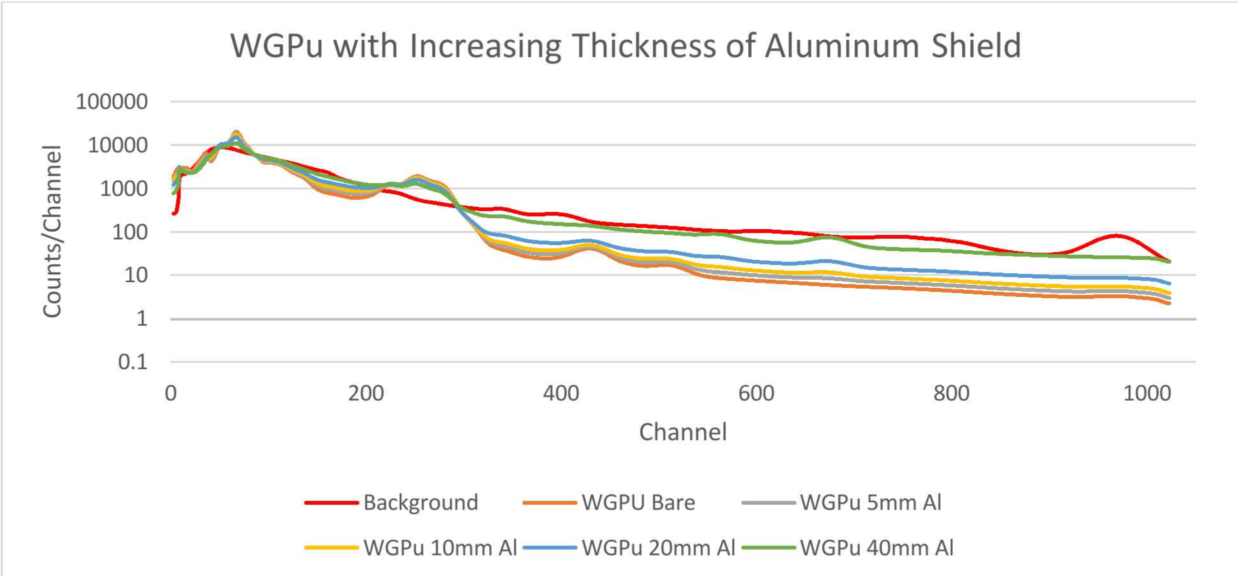

Figure 5 – WGPu spectra with increasing aluminum shielding thickness

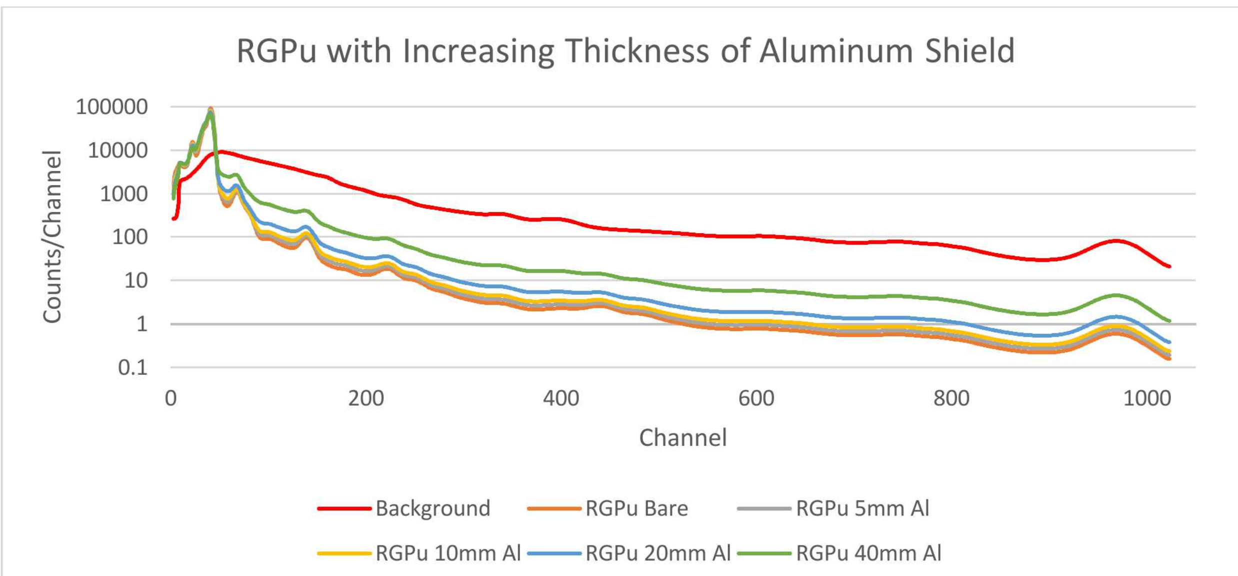

Figure 6 – RGPu spectra with increasing aluminum shielding thickness

By comparing Figures 5 and 6 with Figure 3, it can be observed that significant amounts of aluminum shielding, up to 20 cm of thickness, have a minimal effect on the algorithm's ability to discern between WGPu and RGPu. This consistency in performance can most likely be attributed to the abundance of low energy counts in the RGPu spectra that remain throughout varying shielding thicknesses. Since these frequent low energy counts are not present in the various WGPu spectra, the algorithm has little difficulty in distinguishing between the two samples.

Figure 7 illustrates simulated spectra from HPGe and NaI detectors measuring WGPu and RGPu. The relatively small size of the NaI detector (an IdentiFINDER in this case) results in a termination of counts just above the 1600keV due to calibration.

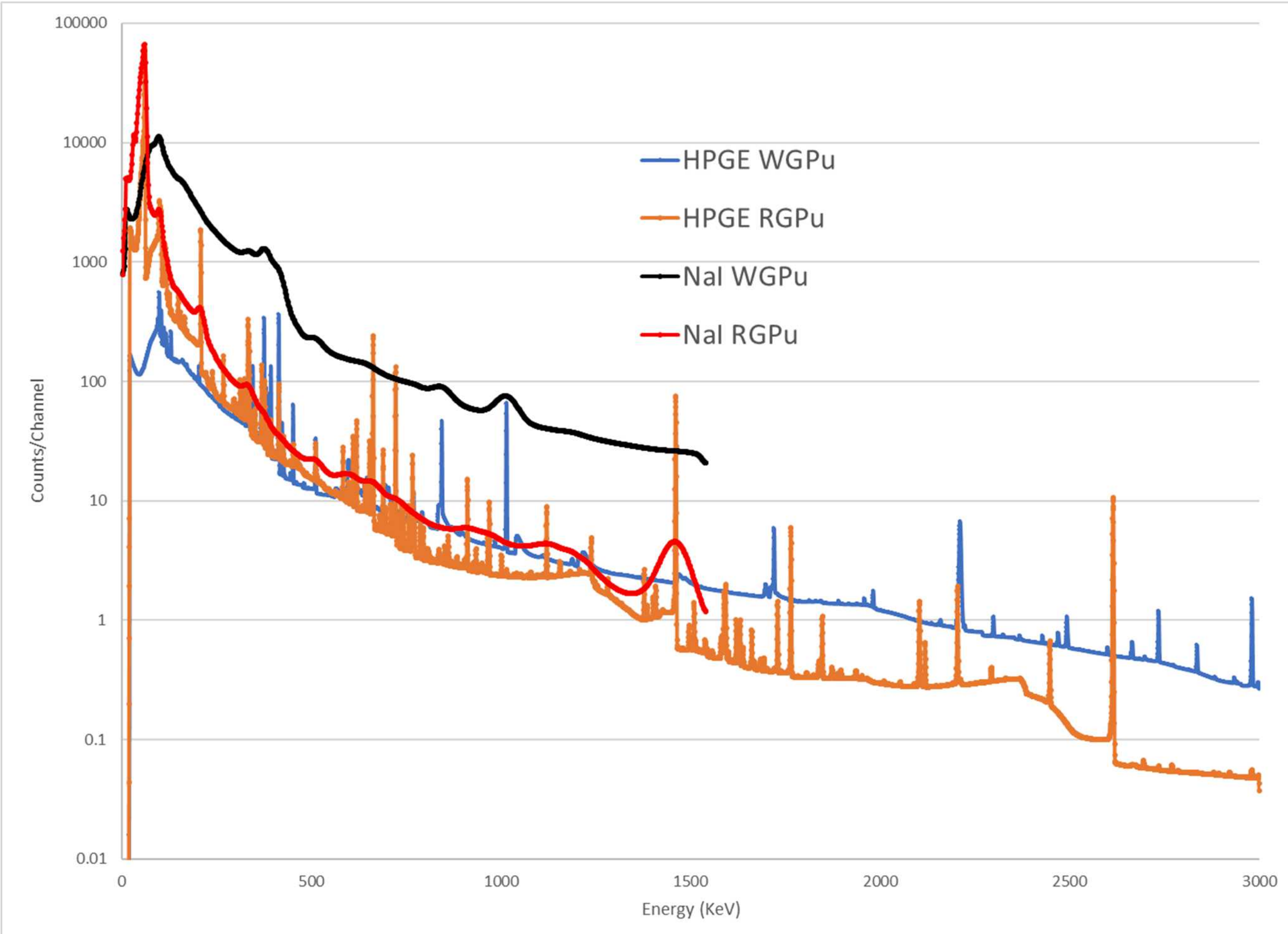

Figure 7 – WGPu vs RGPu Spectra with 40mm Al Thickness

As seen above, the low energy region for RGPu and high energy continuum for WGPu is likely to drive the overall differentiation of algorithm scalar values. More work is needed to precisely identify exact regions of importance for each pair of desired and undesired isotopes. This can also help shed light on other potential mass attribute algorithms.

Figures 8 and 9 below demonstrate this comparison with highly enriched uranium versus low enriched uranium, while Figures 10 and 11 display the medium resolution HEU and LEU spectra compared in Figure 8.

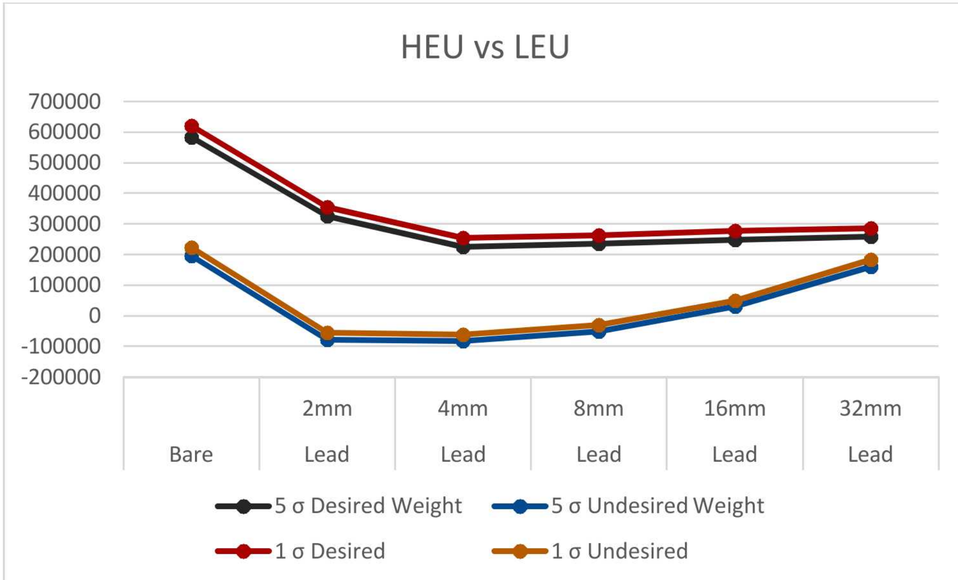

Figure 8 – NaI Detector Scalar Values: HEU versus LEU

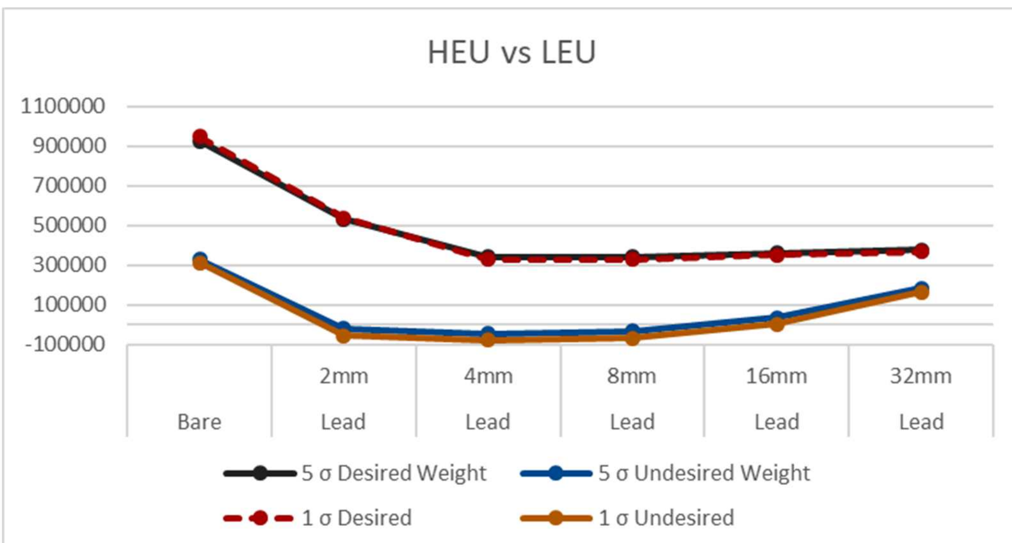

Figure 9 – HPGe Detector Scalar Values: HEU versus LEU

Again, the algorithm’s performance for NaI is comparable to HPGe.

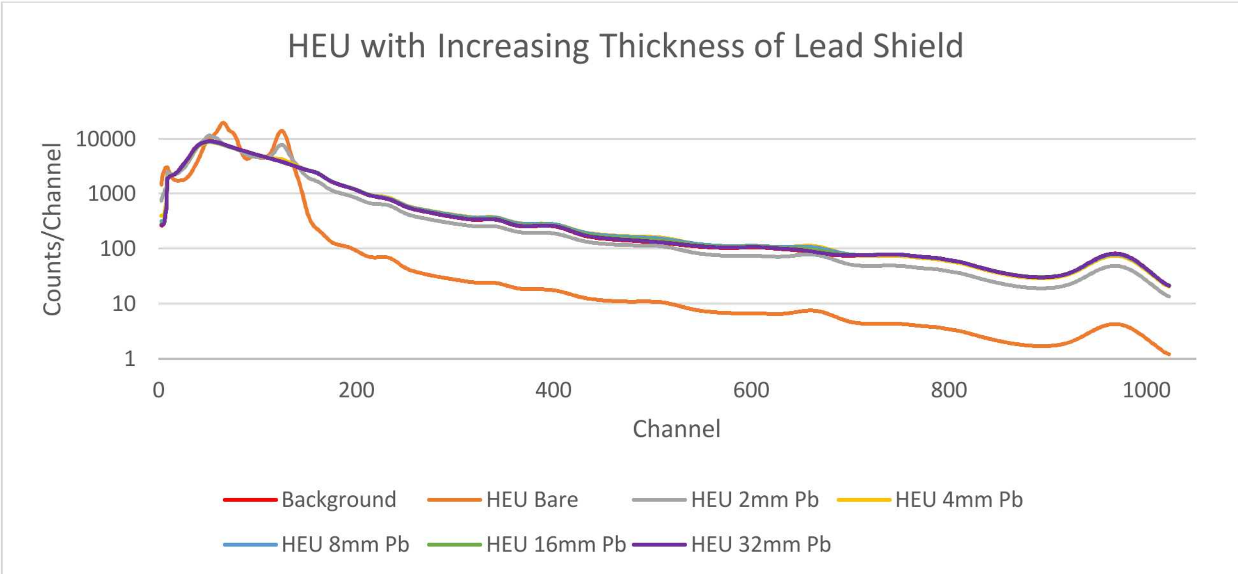

Figure 10 – HEU Spectra with Increasing Lead Shielding Thickness

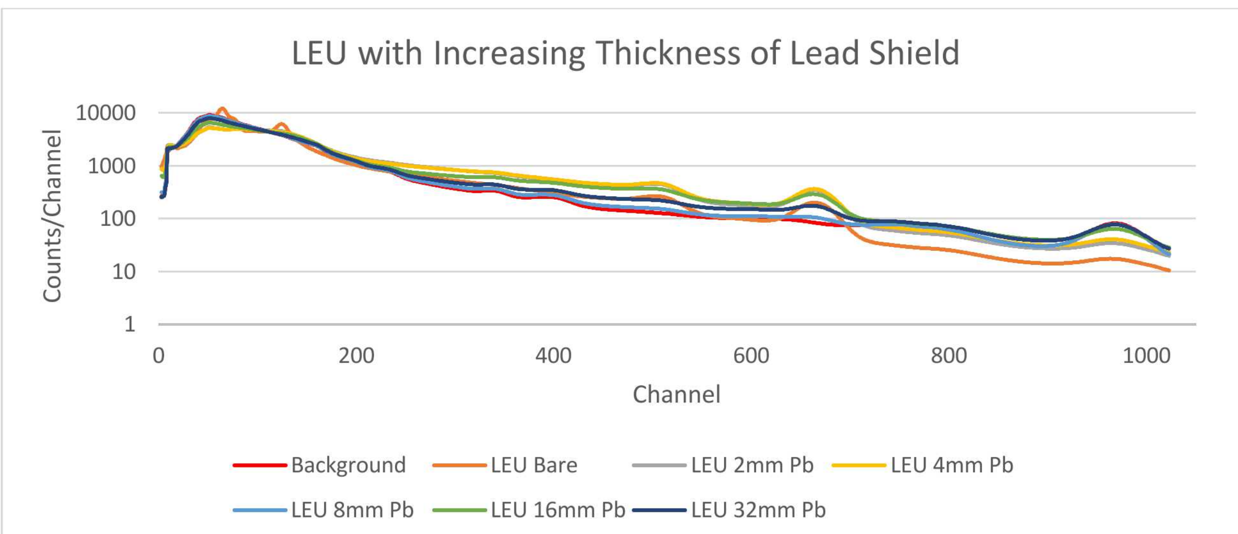

Figure 11 – LEU Spectra with Increasing Lead Shielding Thickness

By comparing figures 10 and 11 with Figure 8, it can be observed that the addition of a high-density lead shield and subsequent increases in thickness will drive a spectrum to resemble that of the background in the area. As both the desired spectra and undesired spectra converge, algorithm performance will be limited. However, as shown in Figure 8, the algorithm has the potential to discern potential material discrepancies, even with the presence of large amounts of shielding.

Further refinement of the algorithm is expected to improve discrimination capabilities and facilitate implementation as a tool for attribute verification in potential future arms control scenarios. Additionally, investigating methods for spectral region importance can help to develop more broadly applicable sets of reduced energy bin resolution without sacrificing algorithm performance. More work is also needed to develop a method for calculating uncertainty in a given measurement using this method.

References

[1] Kallenbach, Gene K., Padilla, Eduardo A., Valencia, Jesus J., "Radioisotope Discrimination Algorithm for Arms Control Inspections," *Institute for Nuclear Materials Management*, July 2018

[2] Mitchell, Dean J., (2015), Gamma Detector Response and Analysis Software: GADRAS 18.6.2.0 [Computer Program], Sandia National Laboratories, Copyright 2014 Sandia Corporation.