Joint Evaluation of Neutron and Gamma-ray multiplicity Analysis for Warhead Attributes

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Abstract

We will present the concept of an attribute measurement system that uses the time-correlated detection of neutron-capture gamma rays together with neutrons to confirm the presence of several warhead attributes concurrently: (1) plutonium mass, (2) multiplication, (3) presence and type of high explosive (HE), and (4) HE thickness. This combination of attributes is especially useful for confirming the presence of a warhead and can also be used to confirm the dismantlement of a warhead (i.e., HE has been separated from the special nuclear material (SNM)).

We will present results from recent demonstrations that were conducted with a capture-gamma multiplicity prototype comprising an array of eight 4”x4”x4” NaI detectors coupled to photomultiplier tubes (PMTs) together with a pair of MC-15 neutron multiplicity counters. Data acquired in a parametric study using a 4.5kg sphere of weapons-grade plutonium (the BeRP ball) moderated by various thicknesses of high-density polyethylene (HDPE) indicate that evaluating SNM mass and assembly multiplication as a function of thickness-dependent efficiency results in an agreement between neutron multiplicity data and capture-gamma multiplicity data at the correct thickness of moderating material. Additional measurements using mock-HE also demonstrate that the mass and multiplication can be reasonably estimated (relative to an MC-15) using correlated capture-gamma data indicating that this can be extended to warhead confirmation.

This joint analysis technique promises to provide higher confidence than more traditional SNM mass attributes methods. For example, in addition to confirming that the total Pu mass present is greater than a threshold of 500g, this capability could potentially also assert that the multiplication is less than threshold *X* and/or greater than threshold *Y*, the HE signature is consistent with composition-*Z* (based on the capture-gamma spectrum), and the HE thickness is greater than *T*.

Introduction

We have previously presented results validating the concept of neutron capture gamma-ray multiplicity (NCGM) analysis (1). It was demonstrated that the time-correlated signatures of neutrons within assemblies of special nuclear material is preserved in the gamma rays emitted from the capture of neutrons by light elements (e.g., hydrogen) in surrounding materials. For example, each neutron captured

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by hydrogen emits a single 2.2 MeV gamma ray. At this energy, the probability of a hydrogen capture gamma ray leaking out of a low-Z moderator is high; including the measurement of these capture gamma rays can complement the measurement of neutron leakage signals.

Here, we explore a combined multiplicity analysis using both neutron capture gamma-rays and fast neutrons. It should be the case that both analyses will independently produce the same solutions for the Pu-240 mass and multiplication using traditional multiplicity analysis, however when the absolute efficiency of either measurement is poorly known, the solutions are not well bounded and uncertainties in these derived quantities can be large. In this study, we make no assumptions about the efficiency of either system, but hypothesize that when their solutions agree, the correct efficiency has been found. In this way, several attributes can be simultaneously derived: (1) Plutonium mass, (2) multiplication, (3) thickness of moderating material, (4) composition of moderating material.

Measurements

The measurement systems employed for these validating measurements were:

1. Eight NaI(Tl) detectors with 4x4x4 in.^{3} crystals shielded by 0.48 cm of lead backed by 0.16 cm of tin and coupled to Burle S83049 photomultiplier tubes arranged in two banks of 2x2 arrays, which are depicted in Figure 1. Each bank of detectors was positioned so that the front of each array was located 50 cm radially from the items being measured. During the measurements, data was acquired using only seven of the NaI(Tl) detectors as the eighth channel on the digitizer was re-purposed to acquire time synchronized data from the neutron detectors.
2. Two MC-15 multiplicity counters (2) 46 cm center to center from the items being measured. TTL signals were streamed to the same data acquisition system as the gamma-ray detectors; an eight-channel, 14-bit, 250 MHz, CAEN DT5725S digitizer with CAEN Digital Pulse Processing – Pulse Height Analysis (DPP-PHA) firmware was used for on-board waveform analysis (3).

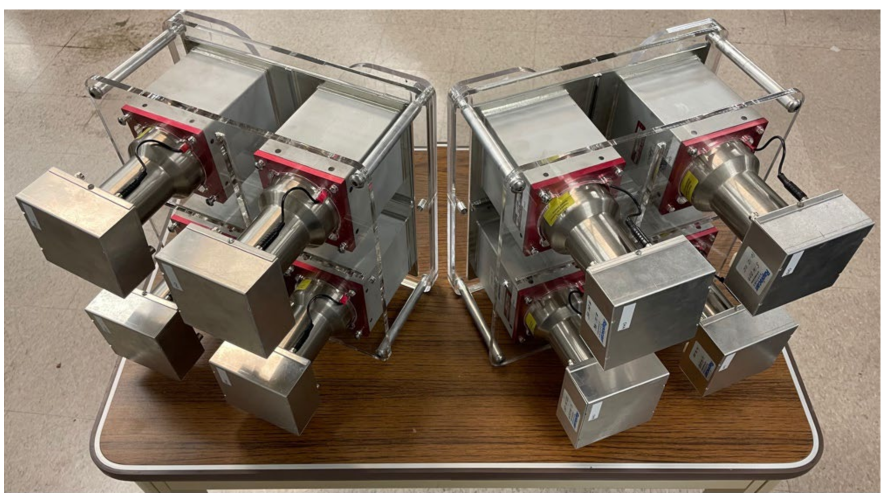

Figure 1. Photo of NaI(Tl) detector arrays used in this work. Each array consists of four 4x4x4 in.^{3} crystals coupled to Burle S83049 photomultiplier tubes. Detectors are shielded in front with 0.48 cm of lead backed by 0.16 cm of tin to reduce the contribution of low energy counts.

To demonstrate this methodology, we analyzed data collected from the Beryllium Reflected Plutonium (BeRP) ball, a 4.5 kg sphere of a-phase weapons-grade plutonium, enveloped in varying thicknesses of HDPE shells (4). The BeRP ball was enclosed in polyethylene shells that were configured to create five different thicknesses of 2”, 3”, 4”, 5”, and 6”, using a set of nested shells each 0.5” in thickness.

Methodology

The key to this method is that the absolute neutron detection efficiency of a neutron capture gamma-ray detector has a significantly different dependence on the thickness of moderating material than does a fast neutron detector. To estimate the efficiency of the two MC-15s, we modeled each of the measured configurations in MCNPX (5). The efficiency of the NaI array was estimated by:

1. Estimating the total number of neutrons produced by the BeRP ball over the 1800 second dwell time of the measurement
2. Modeling the response of the NaI array using the Gamma Detector Response and Analysis Software (GADRAS (6)) inject creator
3. Integrating the counts found in an energy window (2080 keV – 2390 keV) around the 2.2 MeV neutron hydrogen capture gamma-ray
4. Dividing those counts by the total neutrons generated

To estimate the total number of neutrons generated by the BeRP ball, we estimated that the total mass of Pu-240 (the primary spontaneous fission source) is 266.35 grams. At 481.7 fissions/s/gram of Pu-240, we estimate 1.283e5 spontaneous fissions per second total. For each one of these fissions, there will be an average number of 2.16 neutrons produced. Because this is a multiplying source, there are also M-1 more fissions induced in Pu-239 (where M is the multiplication of the system). For each of these, an average of 2.88 neutrons are produced. The total number of neutrons is then given by:

$$N_{Total} = 1.283e5\frac{fissions}{second} * 1800\ seconds * (2.16 + (M-1) * 2.88) \qquad \text{Eq. 1}$$

As can be seen in. *Figure 2*, the fast neutron detector's efficiency steadily falls as the thickness of HDPE surrounding a neutron source increases, whereas a neutron capture gamma-ray system's efficiency rises at low thicknesses and is relatively flat at higher thicknesses. It can also be seen that any uncertainty in the thickness of intervening moderating materials in an object being measured can lead to a large uncertainty in the detection efficiency of the system.

By simultaneously analyzing data collected by both systems as a function of assumed moderator thickness, the correct solution is found at the thickness where the derived parameters, mass and multiplication, are equal.

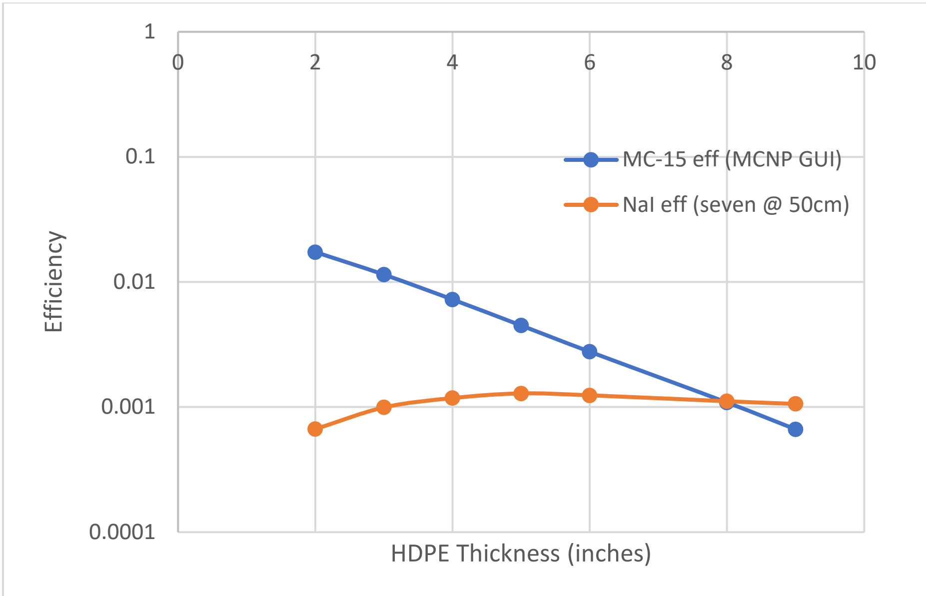

Figure 2 – The absolute efficiency of two MC-15s at 46 cm away (blue) and seven 4" NaI detectors 50 cm away (orange) from the center of a plutonium object, as a function of the thickness of high-density polyethylene (HDPE) shell surrounding the plutonium.

Results and Discussion

For each thickness of HDPE, the multiplication was estimated using a model in GADRAS. The results are listed in Table 1 and plotted in Figure 2.

Table 1 – The estimated multiplication and absolute efficiencies as a function of HDPE thickness around the BeRP ball

HDPE thickness (inches)	Multiplication	Total neutrons generated	Total neutrons detected (2080-2390 keV)	NaI array efficiency	MC-15 efficiency (MCNP)
2	8.58	5540377306	3692621	0.000666493	0.017347
3	9.88	6405022024	6363404	0.000993502	0.011458
4	10.25	6651113213	7848844	0.00118008	0.0072463
5	10.334	6706982564	8625032	0.001285978	0.004489
6	10.33	6704322119	8327536	0.001242115	0.00277
8	10.34	6710973232	7468193	0.001112833	0.001088
9	10.34	6710973232	7113860	0.001060034	0.0006642

For each of the measured data sets, 2"-6" HDPE, we ran a multiplicity analysis using Momentum (7), a software package developed by Los Alamos National Laboratory that is used for neutron multiplicity analysis with the MC-15. Each of the efficiencies estimated in Table 1 were used for both the MC-15s and NaI array. The results are shown in Figure 3 through Figure 7. It can be seen that in all cases, the solutions cross at very nearly the correct thickness of HDPE.

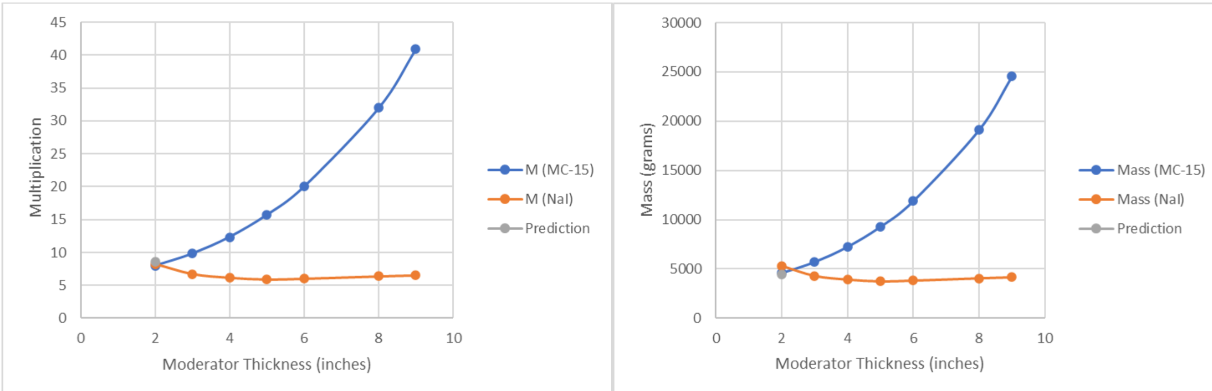

Figure 3 – The estimated multiplication (left) and total mass (right) from measurements made of the BeRP ball surrounded by a 2"-thick shell of HDPE using two MC-15 detectors (blue) and seven 4"x4"x4" NaI detectors (orange).

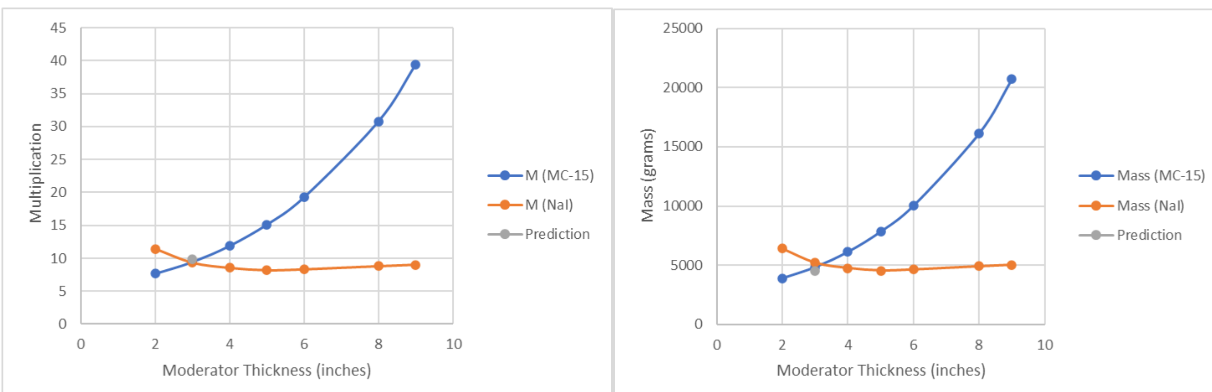

Figure 4 – The estimated multiplication (left) and total mass (right) from measurements made of the BeRP ball surrounded by a 3"-thick shell of HDPE using two MC-15 detectors (blue) and seven 4"x4"x4" NaI detectors (orange).

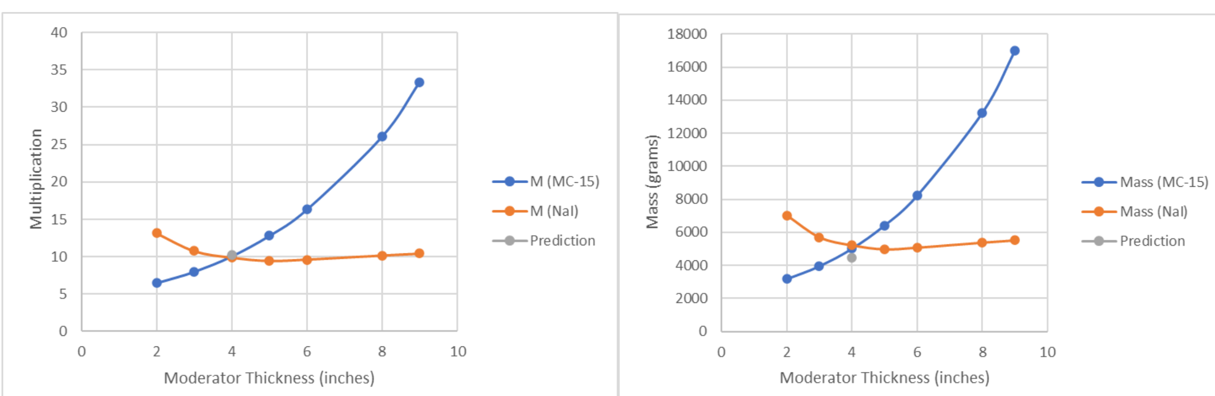

Figure 5 – The estimated multiplication (left) and total mass (right) from measurements made of the BeRP ball surrounded by a 4"-thick shell of HDPE using two MC-15 detectors (blue) and seven 4"x4"x4" NaI detectors (orange).

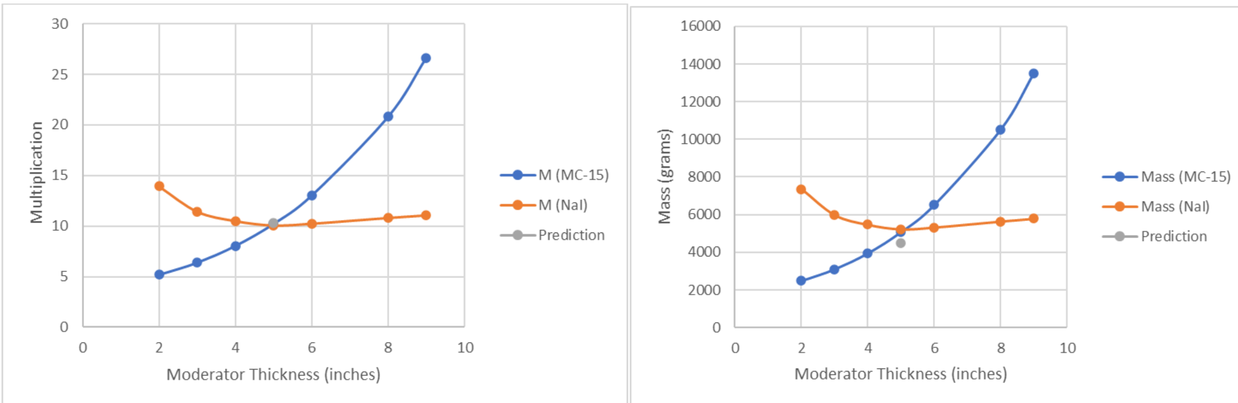

Figure 6 – The estimated multiplication (left) and total mass (right) from measurements made of the BeRP ball surrounded by a 5"-thick shell of HDPE using two MC-15 detectors (blue) and seven 4"x4"x4" NaI detectors (orange).

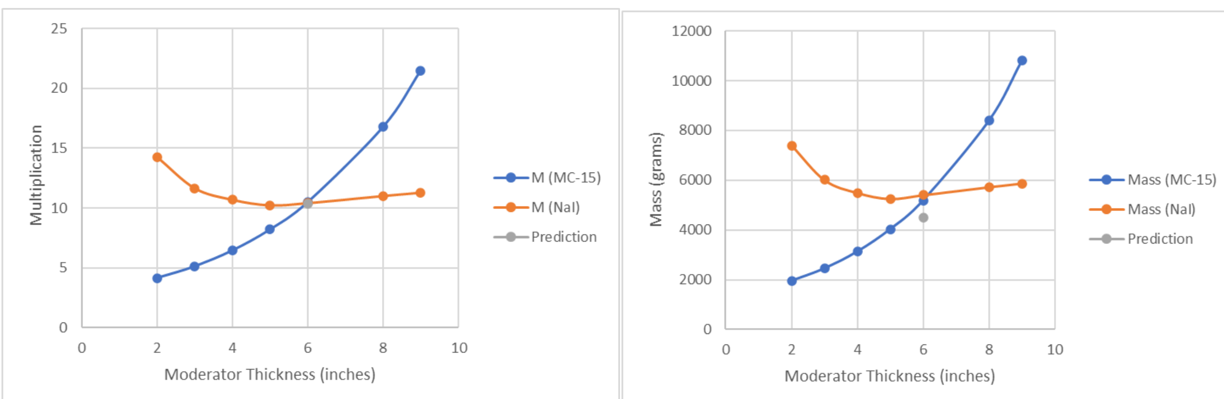

Figure 7 – The estimated multiplication (left) and total mass (right) from measurements made of the BeRP ball surrounded by a 6"-thick shell of HDPE using two MC-15 detectors (blue) and seven 4"x4"x4" NaI detectors (orange).

Table 2 and Table 3 list the multiplication and total mass estimates using the calculated efficiencies at the crossing point of the solutions from the MC-15 and NaI array multiplicity analyses. It can be seen that the estimated multiplication is well consistent between the two analyses and modeling estimates. However, the estimated total Pu mass of both analyses are systematically higher than the true mass of the BeRP ball, but even still within 15% of the correct answer. Though these results leave room for improvement, they are very encouraging. These results suggest it may be possible to estimate mass and multiplication of an unknown assembly without needing to know (or estimate) the efficiency of the specific measurement configuration. Further, this technique also makes it possible to estimate the thickness of the moderating material. While thickness can be obtained in other ways (e.g., through the use of radiography), these estimates can be made quickly and without the need for additional equipment of active interrogation techniques.

Table 2 – The estimated multiplications of the BeRP ball in various thicknesses of HDPE

HDPE thickness (inches)	Multiplication (GADRAS)	Multiplication (MC-15 analysis)	Multiplication (NaI array analysis)
2	8.6	8.0	8.3
3	9.9	9.5	9.3
4	10.3	10.1	9.9
5	10.3	10.2	10.0
6	10.3	10.5	10.4

Table 3 – The estimated total mass of the BeRP ball in various thicknesses of HDPE

HDPE thickness (inches)	Total Pu Mass (grams)	Total Pu Mass (MC-15 analysis)	Total Pu Mass (NaI array analysis)
2	4484	4613	5326
3	4484	4826	5209
4	4484	5011	5219
5	4484	5072	5230
6	4484	5192	5411

Conclusions and Future Work

The methodology demonstrated in this work opens the door for the possibility of a warhead confirmation system for potential future nuclear arms control verification using the time-correlated detection of neutron-capture gamma rays together with neutrons to confirm the presence of several warhead attributes concurrently: (1) plutonium mass, (2) multiplication, (3) presence and type of HE, and (4) HE thickness. This combination of attributes is especially useful for confirming the presence of a warhead and can also be used to confirm the dismantlement of a warhead (i.e., HE has been separated from the SNM).

We have also collected data from the BeRP ball surrounded by a range of thicknesses of mock high explosives (2” – 8”, see Figure 8). Preliminary work has demonstrated that timing correlations are preserved in the capture gammas in this material as well. Future work will include the development of energy selection criteria that account for differences in the MHE spectra (relative to HDPE) and estimates of the absolute efficiencies to demonstrate the methodology for these measurements as well.

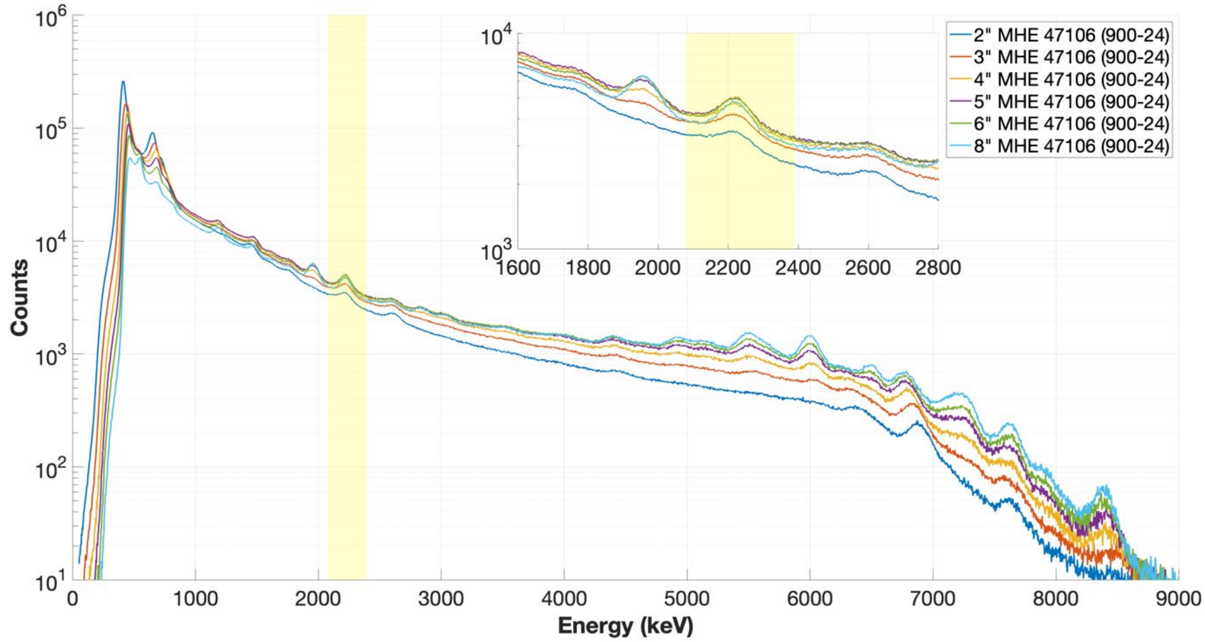

Figure 8. Gamma-ray energy spectra for each of six configurations moderated by mock HE (MHE). Spectra are summed across all seven channels and are scaled for a 600 second measurement. Inset zooms on the 2.2 MeV photopeak originating from neutron capture on hydrogen. Additional high-energy photopeaks are apparent due to thermal capture and inelastic scatters on elements such as nitrogen and chlorine.

With further work, this joint analysis technique promises to provide higher confidence than more traditional SNM mass attributes methods. For example, in addition to confirming that the total Pu mass present is greater than a threshold of 500g, this capability could potentially also assert that the Multiplication is within agreed upper and lower bounds, that the HE signature is consistent with a specified composition (based on the capture-gamma spectrum), and that the HE thickness is within agreed upper and lower bounds.

Acknowledgements

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