

**NIST Technical Note 1808**

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L. Pibida

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*Radiation Physics Division*

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# Report of Special Nuclear Material Validation Measurements for Backpack Type Radiation Detectors

*L. Pibida<sup>1</sup> and C. Ward<sup>2</sup>*

<sup>1</sup> *National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899-8462*

<sup>2</sup> *Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN 37831*

## 1. Introduction

This report provides results and recommendations from the validation testing for the different source configurations and radiation fields produced by special nuclear materials (SNMs) and depleted uranium (DU) listed within the Technical Capability Standard (TCS) for backpack type radiation detectors (BRDs). Testing took place at Oak Ridge National Laboratory (ORNL). Test planning, data analysis, and reporting were performed by the National Institute of Standards and Technology (NIST).

## 2. Measurements Setup

All sources used for testing, including shielding containers, were measured using a calibrated high purity germanium (HPGe) detector. Before beginning testing, a 500 s (live time) background spectrum of the facility was obtained. The sources were then placed at a distance of 1.25 m from the front face of the HPGe detector (same as HPGe calibration distance). A 500 s (live time) gamma-ray spectrum was acquired for each source configuration using the HPGe detector. Measurements of the exposure rate produced by each source configuration were performed at a distance of 35 cm from the left side of the Victoreen 451P-DE-SI<sup>1</sup> (38.8 cm from the reference point of the instrument). A total of 10 independent readings were acquired to determine the mean and standard deviation of the radiation field for each source configuration as well as for the radiation background level.

All the test configurations, testing parameters, and shielding thicknesses used in the tests were recorded. The calculated testing distances were based on the measured emission rates for each source. A summary of these values are listed in Table 1.

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<sup>1</sup> Mention of commercial products does not imply recommendation nor endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

**Table 1: Summary of calculated and required test parameters**

Source	Shielding material	Source thickness (mm)	TCS required fluence rate of the source at reference point ( $s^{-1} cm^{-2}$ )*	Actual Shielding thickness (cm) †	Calculated Testing Distance (cm)	Calculated Testing Speed (m/s)
HEU	None	NA	$0.94 \pm 10 \%$	NA	228.5	1.37
HEU	Lead #1	NA	$0.94 \pm 10 \%$	0.04 (1/64")	228.5	1.37
HEU	Lead #2	NA	$0.94 \pm 10 \%$	0.08 (1/32")	228.5	1.37
HEU	Steel	NA	$0.94 \pm 10 \%$	0.48 (3/16")	228.5	1.37
HEU	HDPE	NA	$0.94 \pm 10 \%$	4.71 (2")	228.5	1.37
HEU	Steel + HDPE	NA	$0.94 \pm 10 \%$	0.32 (1/8") Steel/ 2.53 (1") HDPE	228.5	1.37
WGPu	None	NA	$2.30 \pm 10 \%$	NA	47.0	0.28
WGPu	5 mm copper	NA	$2.30 \pm 10 \%$	5 mm copper	47.0	0.23
WGPu	4.5 mm steel	NA	$2.30 \pm 10 \%$	4.5 mm steel	47.0	0.25
WGPu	8.2 mm steel	NA	$2.30 \pm 10 \%$	8.2 mm steel	47.0	0.19
WGPu	Lead #1	NA	$2.30 \pm 10 \%$	0.24 (3/32")	47.0	0.28
WGPu	Lead #2	NA	$2.30 \pm 10 \%$	0.32 (1/8")	47.0	0.28
WGPu	Steel	NA	$2.30 \pm 10 \%$	0.95 (3/8")	47.0	0.28
WGPu	HDPE	NA	$2.30 \pm 10 \%$	7.98 (3")	47.0	0.28
WGPu	Steel + HDPE	NA	$2.30 \pm 10 \%$	0.48 (3/16") Steel/ 3.78 (1.5") HDPE	47.0	0.28
DU	None	3.175	$0.34 \pm 10 \%$	NA	217.3	1.30

\* Uncertainties have a coverage factor, k, of 1  
† The shielding thickness has an uncertainty of  $\pm 10 \%$  (k=1). Shielding material in the USA is purchase in inches; therefore values in parenthesis provide the actual thickness needed when purchasing this material. Values in SI units are rounded up and based on the actual measured values.

The ORNL sources used for these measurements were:

- 4 Depleted Uranium (DU) plates – source number: U-238-3618, U-238-3621, U-238-3622, U-238-3624
- Highly Enriched Uranium (HEU) sphere – source number: U-234-5879
- Weapons Grade Plutonium (WGPu) cylinder – source number: Pu-239-FP22R9R87

In an effort to reduce the  $^{241}\text{Am}$  contribution of the WGPu source, three cylindrical shielding containers were also tested (4.5 mm steel, 5 mm copper, and 8.2 mm steel).

Three BRDs were used for the measurements, two with gross count detection capabilities (refer to here

as BRD1 and BRD2) and one with radionuclide identification capabilities (refer to here as BRD3). According to the BRD TCS, the testing parameters depend on the instrument's operational mode. The following parameters were used for these tests:

1. **Static Mode:** collection time for radionuclide identification was set for 60 seconds.
2. **Dynamic Mode:** the source was mounted at the back of the vehicle (Kubota), see Figure 1. The vehicle speed could not be easily controlled but the two available speeds were  $2.14 \pm 0.08$  m/s and  $1.07 \pm 0.07$  m/s.

A phantom was placed behind each backpack, see Figure 2. The phantom dimensions were 40 cm wide, 60 cm high and 15 cm thick. Measurements were performed with the front part of the BRD facing the source; the BRD was not rotated relative to the source direction.

The static measurements were performed indoors. The BRDs were mounted on a stand in front of the phantom with the center of the BRD placed at a distance of 1.5 from the floor, see Figure 2. The source was mounted on a table and the source center was aligned with the BRD center. Each source was placed in front of each BRD at the required distance, see Table 1. For each test, the instrument was exposed to a source listed in Table 1, the gamma and neutron readings were obtained (10 readings each), and when applicable, identified radionuclides were recorded. For BRDs with spectrometric capabilities, one 60 second spectra for each source configuration was acquired and saved.

The dynamic measurements were performed outdoors. The BRDs were mounted on a stand in front of the phantom with the center of the BRD placed at a distance of 1.2 m from the floor. The source was mounted at the back of the vehicle (Kubota) and the source center was aligned with the BRD center, see Figure 1. The vehicle speed could not be easily controlled but the two available speeds were  $2.14 \pm 0.08$  m/s and  $1.07 \pm 0.07$  m/s. The required speeds are listed in Table 1. Only 5 trials were performed for the BRD radionuclide identification capabilities due to impending weather conditions. The testing distance for the WGPu sources was 80 cm at a speed of 1.07 m/s. The HEU and DU sources were tested at 2.14 m/s. The testing distances for HEU and DU were 228 cm and 217 cm respectively; same distances as used for the static measurements.

For dynamic measurements only, three sheets of gauge 28 galvanized tin were used in an attempt to reduce the  $^{241}\text{Am}$  contribution to the total signal.



**Figure 1: Source mounting for dynamic tests**



**Figure 2: BRD mounting on phantom and source location relative to BRD**

The measured environmental conditions during testing are listed in Table 2.

**Table 2: Environmental conditions during testing**

Measurement location	Temperature (°C)	Relative humidity (%)	Atmospheric pressure (mm of Hg)
Indoor minimum value	22.9	52.0	740.6
Indoor maximum value	24.0	60.8	741.0
Outdoor minimum value	29.5	54.5	734.8
Outdoor maximum value	32.2	65.5	736.7

### 3. Shielding

The shielding thicknesses specified in the BRD TCS (see Table 3) could not be acquired from any material manufacturer. Therefore, it was decided to either purchase commercial available material closest to thicknesses as specified in the TCS or purchase thicker material and machine it to the required TCS value. In order to reduce the cost of the tests, it was decided to purchase commercial available material with the closest thicknesses as specified in the TCS. However, this meant the material thicknesses changed by a significant amount for both the lead and the high density polyethylene (HDPE). For the lead shielding, the difference was between 12 % and 21 % depending on the source and shielding thickness, therefore two different thicknesses were acquired for each source in order to assess the differences in response. Due to the properties of the HDPE, the material was welded together to form boxes. Table 3 also lists the actual thicknesses used for the testing.

**Table 3: Shielding thicknesses**

Source	Shielding material	TCS Shielding thickness (cm) †	Actual Shielding thickness (cm) *†
HEU	Lead	0.05	0.04/0.08
HEU	Steel	0.53	0.48
HEU	HDPE	5.37	4.71
HEU	Steel + HDPE	0.26 Steel/2.68 HDPE	0.32 Steel/2.53 HDPE
WGPu	Lead	0.27	0.24/0.32
WGPu	Steel	1.00	0.95
WGPu	HDPE	7.18	7.98
WGPu	Steel + HDPE	0.5 Steel/3.59 HDPE	0.48 Steel/3.78 HDPE
† The shielding thickness has an uncertainty of $\pm 10\%$ ( $k=1$ )			
* Values in SI units are rounded up and based on the actual measured values.			

In addition to the TCS specified shielding materials and thickness, ORNL built three cylindrical shielding containers intended to be used to reduce the <sup>241</sup>Am contribution of the WGPu source. The containers



included a 4.5 mm thick steel, a 5 mm thick copper, and an 8.2 mm thick steel cylinders. These cylinders were also used with the WGPu source.

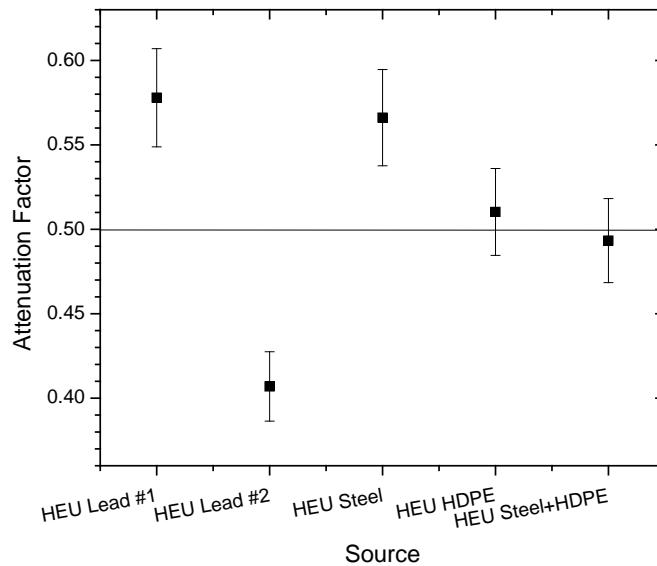
## 4. Calculations and Measurements

### 4.1 Attenuation Factor

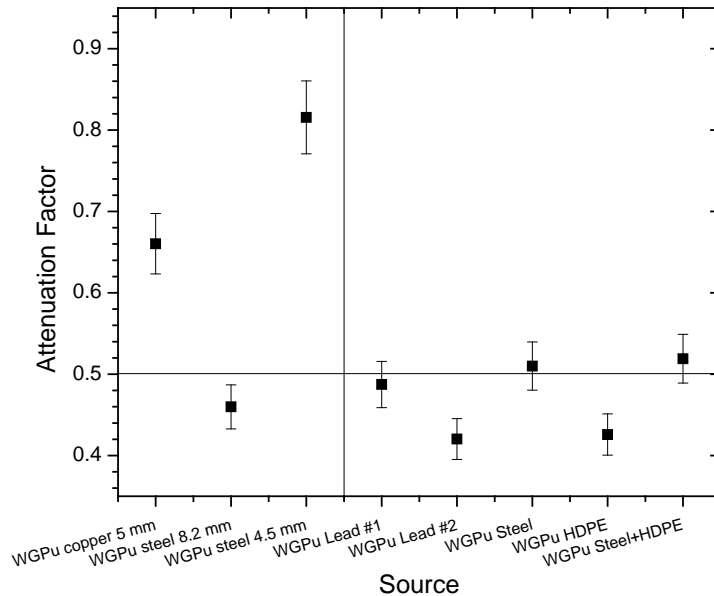
The HPGe measurements for each source configuration were used to obtain the attenuation factors produced by the different shielding materials and thicknesses as well as the corresponding fluence rates. The attenuation factor is defined as the ration between the emerging photon beam intensity,  $I$ , after going through a layer of material with thickness,  $x$ , and density,  $\rho$ , divided by the incident photon beam intensity,  $I_0$ , see equation 1.

$$\frac{I}{I_0} = \exp[-(\mu/\rho)x\rho] \quad (1)$$

where  $\mu/\rho$  is the mass attenuation coefficient. The BRD TCS standard requires an attenuation factor of 0.5 for all sources but the actual attenuation values varied between 0.40 and 0.58 depending on the source and shielding material thickness. These values were obtained for the 185.72 keV line for HEU, 413.71 keV for WGPu, and 1001.03 keV for DU sources. Figure 3 for HEU and Figure 4 for WGPu show the required (0.5) and the actual attenuation factor for each shielding material.



**Figure 3: Attenuation factors for 185.72 keV photopeak from HEU source. Uncertainties are one standard deviation.**



**Figure 4: Attenuation factors for 413.71 keV photopeak from WGPu source. The points to the left of the vertical line are the measured values using the ORNL cylinders. Uncertainties are one standard deviation.**

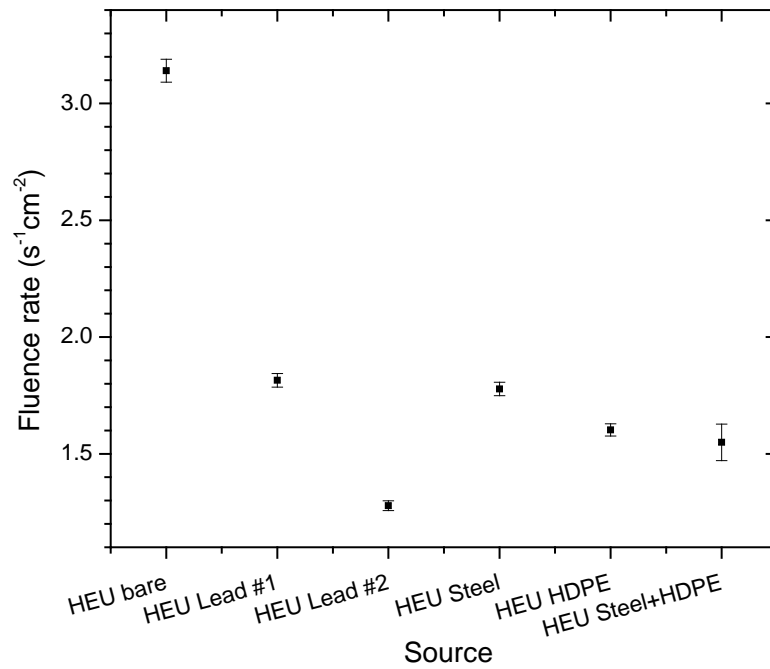
In Figure 4 the measured attenuation factors, calculated as the ratio of the measured fluence rate for the shielded WGPu source divided by the fluence rate for the bare WGPu source rate, for the cylindrical steel containers (4.5 mm and 8.2 mm thick) do not follow the expected exponential attenuation law. This can be explain by the fact that the source does not fit tightly within the cylinders so the source-to-detector distance cannot be precisely set when using these shielding containers.

## 4.2 Fluence Rate

The TCS defines the fluence rates based on the emission of specific photon energies for the various sources; it does not define the total fluence rate of the source based on all the emitted photon energies. The fluence rates reported here are based on the emission of specific photon energies for the various sources.

The fluence rates were measured at a source-to-detector distance of 1.25 m using the HPGe detector for all shielding configurations. The HPGe measurements can be performed at any distance as long as the full-energy peak efficiency of the HPGe detector is known at the measurement distance. The measured fluence rate values are shown in Figure 5 for HEU and in Figure 6 for WGPu. The measured fluence rate for the bare DU source (4 plates) was 1.028 gammas/s/cm<sup>2</sup>. All fluence rate values were obtained for the 185.72 keV line for HEU, 413.71 keV for WGPu, and 1001.03 keV for DU sources. However, the 59.54 keV line for <sup>241</sup>Am in the WGPu spectra was always measureable except when the source was placed inside the lead shielding containers. The measured fluence rates for the different WGPu source containers are listed in Table 4. Figure 7 and Figure 8 show the 500 s live time spectra for the WGPu source shielded by different materials and material thicknesses. From these figures; the reductions of the <sup>241</sup>Am 59.54 keV

peak relative to the 413.71 keV peak of the  $^{239}\text{Pu}$  is displayed. The  $^{241}\text{Am}$  59.54 keV peak is not measurable when shielded with lead. When shielded by HDPE, the  $^{241}\text{Am}$  59.54 keV peak displays a large low-energy tail mainly due to scattering within the shielding material.



**Figure 5: Fluence rates for HEU source. Uncertainties are one standard deviation.**

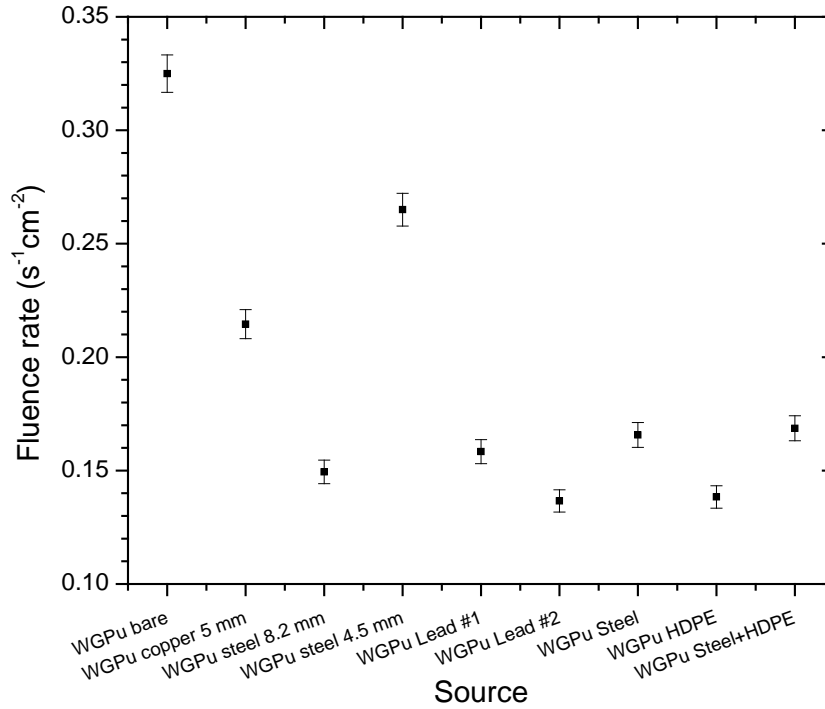


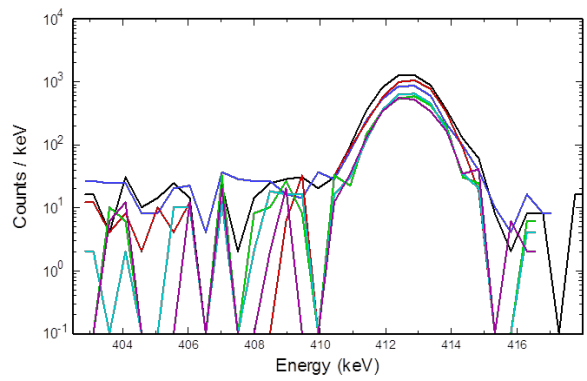
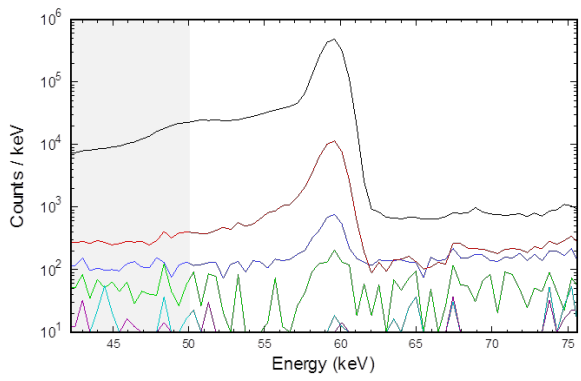
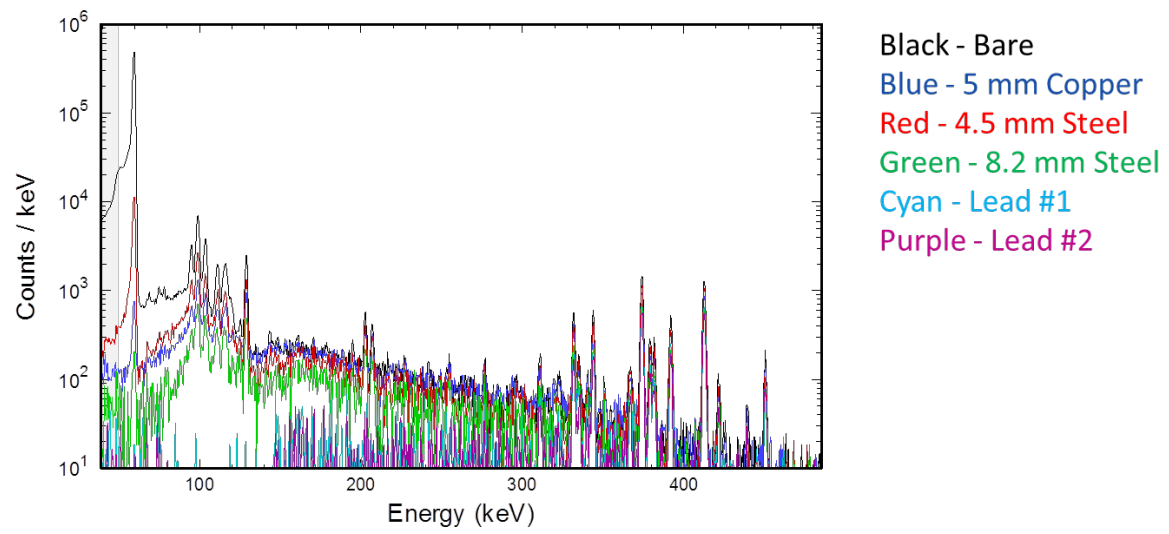
Figure 6: Fluence rates for WGPu source. Uncertainties are one standard deviation.

Table 4: Measured fluence rates and ratios for WGPu gamma-ray lines at 1.25 m

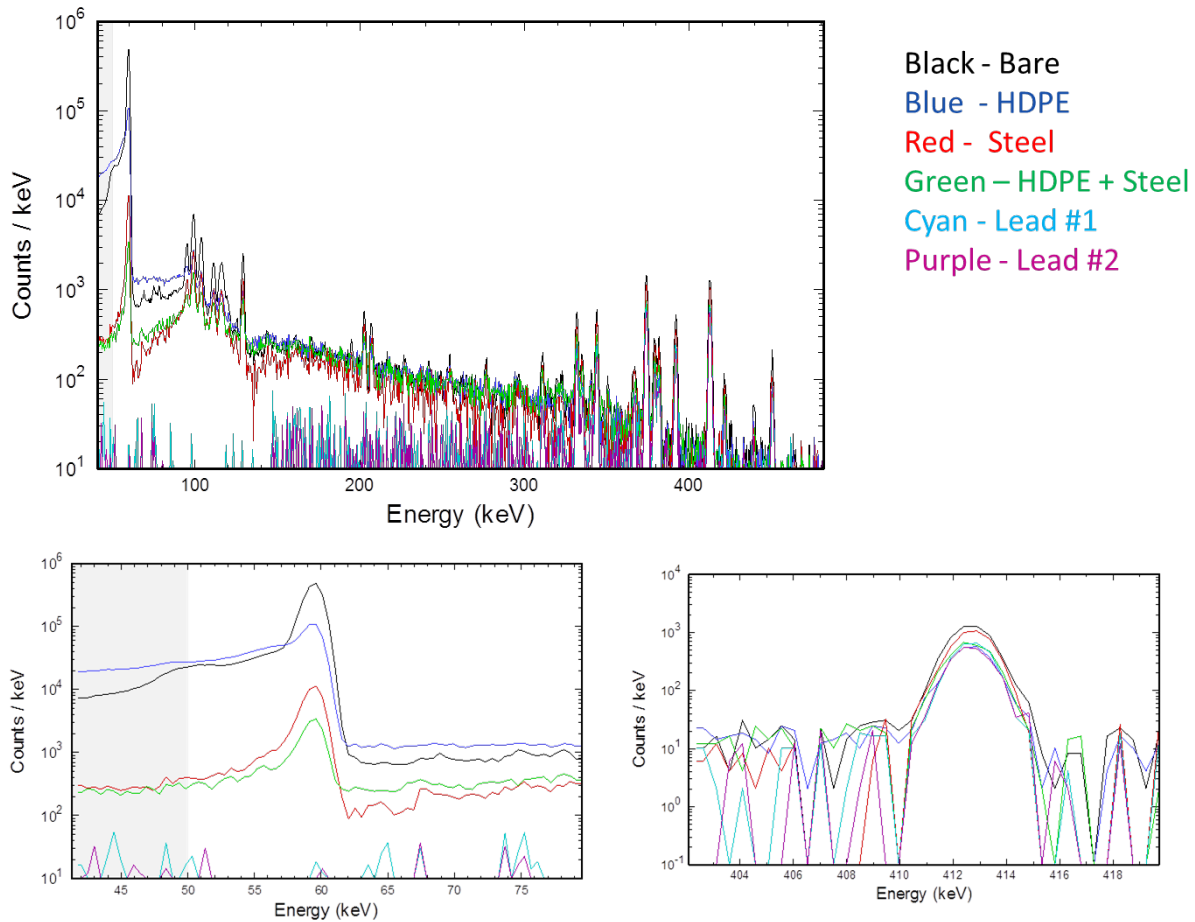
Source	Shielding	Fluence rate of 59.54 keV (s <sup>-1</sup> cm <sup>-2</sup> )	Fluence rate of 413.71 keV (s <sup>-1</sup> cm <sup>-2</sup> )	Ratio (59.54/413.71 keV)
WGPu	None	73.51 ± 3.68	0.325 ± 0.008	226.2
WGPu	5 mm copper	0.096 ± 0.006	0.215 ± 0.006	0.448
WGPu	4.5 mm steel	1.77 ± 0.09	0.265 ± 0.005	6.691
WGPu	8.2 mm steel	0.028 ± 0.004	0.149 ± 0.007	0.186
WGPu	Lead #1	0	0.158 ± 0.005	0
WGPu	Lead #2	0	0.137 ± 0.005	0
WGPu	Steel	0.016 ± 0.003	0.166 ± 0.005	0.098
WGPu	HDPE	17.09 ± 0.86	0.138 ± 0.005	123.51
WGPu	Steel + HDPE	0.504 ± 0.026	0.169 ± 0.006	2.989

Uncertainties have a coverage factor, k, of 1

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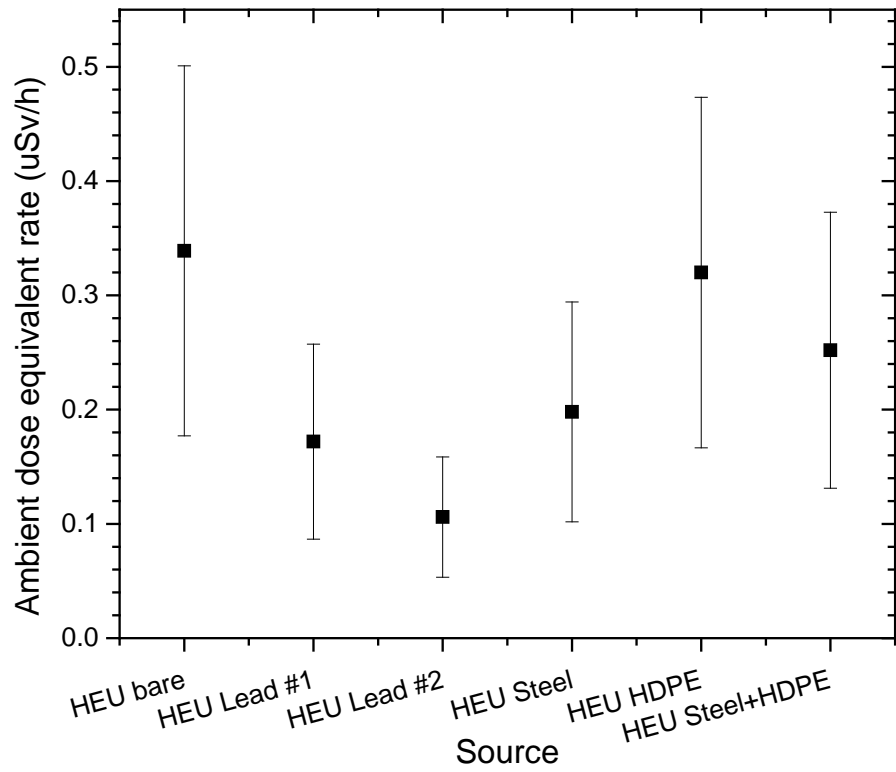
**Figure 7: HPGe spectra showing the plutonium source placed inside different shielding materials used to reduce the emission from the americium peak**



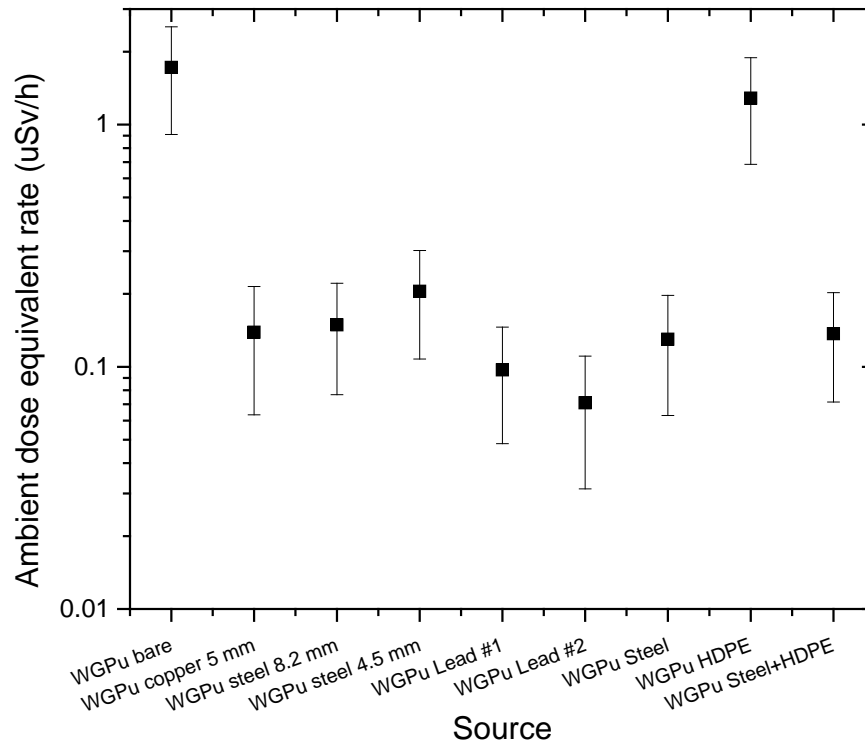
**Figure 8: HPGE spectra showing the plutonium source placed inside different shielding materials**

### 4.3 Ambient Dose Equivalent Rate

The ambient dose equivalent rate for HEU and WGPu measured by the Victoreen 451P-DE-SI at a distance of 35 cm from the left side of the instrument (38.8 cm from the reference point of the instrument) is plotted in Figure 9 and Figure 10. The main contribution to the ambient dose equivalent rate for the WGPu is coming from the  $^{241}\text{Am}$  content in the source.



**Figure 9: Ambient dose equivalent rate measured for the HEU source. Uncertainties are one standard deviation.**



**Figure 10: Ambient dose equivalent rate measured for the WGPu source. Uncertainties are one standard deviation.**

## 5. BRD Measurement Results

The results of the gamma and neutron readings, and radionuclides identified (when applicable) for the static and dynamic measurements are summarized in Table 5 through Table 9. The uncertainties are the standard deviation of the mean value of the 10 static trials or 5 dynamic trials. The results of the static 60 second dwell measurements for the BRD with radionuclide identification capabilities are summarized in Table 8. In Table 7 and Table 9 the numbers in parenthesis represent the number of trials for which a given radionuclide was identified. When there were no radionuclides identified it is summarized as “No ID”.



**Table 5: Results of gamma and neutron readings for BRD1 - Static**

<b>Source</b>	<b>Actual Shielding thickness (cm) †</b>	<b>Gamma Level*</b>	<b>Neutron Level*</b>
Background	None	0 ± 0	1.0 ± 0.7
HEU	None	1 ± 0	1.8 ± 0.4
HEU + Lead #1	0.0397	0 ± 0	0.9 ± 0.7
HEU + Lead #2	0.0794	0 ± 0	0.8 ± 0.9
HEU + Steel	0.4763	1 ± 0	0.8 ± 0.4
HEU + HDPE	4.7142	1.1 ± 0.3	0.5 ± 0.5
HEU + Steel+ HDPE	0.3175 Steel/ 2.5286 HDPE	0 ± 0	0.2 ± 0.6
WGPu	None	4 ± 0	0.3 ± 0.7
WGPu	None (with 5 mm copper)	2 ± 0	0.7 ± 0.7
WGPu	None (with 4.5 mm steel)	2 ± 0	1.2 ± 0.4
WGPu	None (with 8.2 mm steel)	2 ± 0	1.3 ± 0.7
WGPu + Lead #1	0.2381	1 ± 0	0.9 ± 0.9
WGPu + Lead #2	0.3175	1 ± 0	1.2 ± 0.9
WGPu + Steel	0.9525	1.9 ± 0.3	0.5 ± 0.5
WGPu + HDPE	7.9794	4 ± 0	1.4 ± 0.5
WGPu + Steel+ HDPE	0.4763 Steel/ 3.7833 HDPE	2 ± 0	1.3 ± 0.5
DU	None	1 ± 0	0.7 ± 0.7
Uncertainties have a coverage factor, k, of 1			
† The shielding thickness has an uncertainty of ± 10 % (k=1)			
* The ranges of the levels are 0 to 10			

**Table 6: Results of gamma and neutron readings for BRD2 - Static**

Source	Actual Shielding thickness (cm) †	Gamma Level*	Neutron Level*	Net Gamma reading (cps)	Net Neutron reading (cps)
Background	None	0 ± 0	0 ± 0	41.1 ± 10.6	0.9 ± 0.16
HEU	None	4.8 ± 0.9	0 ± 0	130.9 ± 15.7	1.0 ± 0.16
HEU + Lead #1	0.0397	2.9 ± 0.7	0 ± 0	62.5 ± 9.6	1.6 ± 0.7
HEU + Lead #2	0.0794	2.1 ± 1.1	0 ± 0	43.7 ± 9.1	1.26 ± 0.13
HEU + Steel	0.4763	3.5 ± 1.1	0 ± 0	68.5 ± 7.3	1.09 ± 0.11
HEU + HDPE	4.7142	5.5 ± 0.5	0 ± 0	114.9 ± 16.5	1.19 ± 0.17
HEU + Steel+ HDPE	0.3175 Steel/ 2.5286 HDPE	3.5 ± 0.8	0 ± 0	80.9 ± 7.4	1.15 ± 0.14
WGPu	None	9 ± 0	0 ± 0	10058 ± 336	1.23 ± 0.17
WGPu	None (with 5 mm copper)	8 ± 0	0 ± 0	399 ± 24	1.54 ± 0.16
WGPu	None (with 4.5 mm steel)	8.8 ± 0.4	0 ± 0	632 ± 49	1.20 ± 0.13
WGPu	None (with 8.2 mm steel)	8 ± 0	0 ± 0	319 ± 27	1.05 ± 0.18
WGPu + Lead #1	0.2381	5.1 ± 0.7	0 ± 0	112.5 ± 19.2	1.08 ± 0.12
WGPu + Lead #2	0.3175	4.9 ± 0.74	0 ± 0	108.6 ± 13.5	1.84 ± 0.39
WGPu + Steel	0.9525	7.6 ± 0.52	0 ± 0	300.5 ± 12.6	1.17 ± 0.20
WGPu + HDPE	7.9794	9 ± 0	0.2 ± 0.6	8491 ± 148	1.55 ± 0.66
WGPu + Steel+ HDPE	0.4763 Steel/ 3.7833 HDPE	8 ± 0	0.4 ± 0.70	578 ± 31	1.84 ± 0.68
DU	None	5.6 ± 0.5	0 ± 0	140.1 ± 12.4	1.33 ± 0.27
Uncertainties have a coverage factor, k, of 1					
† The shielding thickness has an uncertainty of ± 10 % (k=1)					
* The ranges of the levels are 0 to 9					

**Table 7: Results of gamma and neutron readings, and radionuclides identified for BRD3 - Static**

Source	Actual Shielding thickness (cm) †	Gamma Level*	Neutron Level*	Net Gamma reading (cps)	Net Neutron reading (cps)	Radionuclides Identified
Background	None	0 ± 0	0 ± 0	230 ± 5	3.8 ± 1.1	No ID (10)
HEU	None	7 ± 0	0 ± 0	337 ± 7	3.8 ± 1.2	U-235 HE (7), No ID (3)
HEU + Lead #1	0.0397	5 ± 0	0 ± 0	162 ± 3	4.4 ± 1.1	Co-57 (1), No ID (9)
HEU + Lead #2	0.0794	4 ± 0	0 ± 0	91.2 ± 1.1	3.7 ± 0.9	No ID (10)
HEU + Steel	0.4763	5.5 ± 0.5	0 ± 0	177 ± 4	4.3 ± 1.2	U-235 HE (3), U-238 (2), Co-57 (1), No ID (4)
HEU + HDPE	4.7142	6 ± 0	0 ± 0	266 ± 23	3.1 ± 0.9	U-235 HE (3), No ID (7)
HEU + Steel+ HDPE	0.3175 Steel/ 2.5286 HDPE	6 ± 0	0 ± 0	202 ± 7	4 ± 1	U-235 HE (7), No ID (3)
WGPu	None	9 ± 0	0 ± 0	15860 ± 549	3.6 ± 1.2	Am-241 (1), No ID (9)
WGPu	None (with 5 mm copper)	9 ± 0	0 ± 0	1260 ± 102	3.4 ± 1	WGPu (2), Pu-240 (1), No ID (7)
WGPu	None (with 4.5 mm steel)	9 ± 0	0 ± 0	1693 ± 19	4.1 ± 0.7	Am-241 (9), No ID (1)
WGPu	None (with 8.2 mm steel)	9 ± 0	0 ± 0	1385 ± 78	4.2 ± 0.9	No ID (10)
WGPu + Lead #1	0.2381	8 ± 0	0 ± 0	582 ± 6	4.2 ± 0.8	WGPu (1), No ID (9)
WGPu + Lead #2	0.3175	7.7 ± 0	0 ± 0	487 ± 7	3.5 ± 1.4	No ID (10)
WGPu + Steel	0.9525	9 ± 0	0 ± 0	936 ± 11	4.3 ± 1.4	No ID (10)
WGPu + HDPE	7.9794	9 ± 0	0 ± 0	12809 ± 50	3.1 ± 0.9	No ID (10)
WGPu + Steel+ HDPE	0.4763 Steel/ 3.7833 HDPE	9 ± 0	0 ± 0	1210 ± 15	3.9 ± 0.7	Am-241 (7), No ID (3)
DU	None	8 ± 0	0.1 ± 0.3	581 ± 8	4.1 ± 1.4	U-238 (3), No ID (7)

Uncertainties have a coverage factor, k, of 1  
† The shielding thickness has an uncertainty of ± 10 % (k=1)  
\* The ranges of the levels are 0 to 9

**Table 8: Results of radionuclide identification for BRD3 – Static (60 s)**

Source	Actual Shielding thickness (cm) †	Radionuclides Identified	Confidence Indication	Filename
Background	None	No ID	NA	2013-06-12T13.00.37.7768.n42
HEU	None	U-235 (HE) (SNM)	97	2013-06-12T13.58.43.1483.n42
HEU + Lead #1	0.0397	Co-57 (Ind) U-235 HE (SNM)	97 73	2013-06-12T14.07.34.7167.n42
HEU + Lead #2	0.0794	U-235 (HE) (SNM)	72	2013-06-12T14.35.58-6786.n42
HEU + Steel	0.4763	U-235 (HE) (SNM)	92	2013-06-12T14.51.57.0532.n42
HEU + HDPE	4.7142	U-235 (HE) (SNM)	78	2013-06-12T14.45.38.3634.n42
HEU + Steel+ HDPE	0.3175 Steel/ 2.5286 HDPE	U-235 (HE) (SNM)	93	2013-06-11T14.57.41.6714.n42
WGPu	None	Am-241 (Ind)	90	2013-06-12T13.38.14.1531.n42
WGPu	None (with 5 mm copper)	No ID	NA	2013-06-12T15.41.44.9130.n42
WGPu	None (with 4.5 mm steel)	Am-241 (Ind)	87	2013-06-12T15.47.43.3741.n42
WGPu	None (with 8.2 mm steel)	Not measured		
WGPu + Lead #1	0.2381	No ID	NA	2013-06-12T15.11.26.0190.n42
WGPu + Lead #2	0.3175	No ID	NA	2013-06-12T15.16.03.4703.n42
WGPu + Steel	0.9525	No ID	NA	2013-06-12T15.21.32.5335.n42
WGPu + HDPE	7.9794	Am-241 (Ind)	72	2013-06-12T15.27.07.7509.n42
WGPu + Steel+ HDPE	0.4763 Steel/ 3.7833 HDPE	Am-241 (Ind)	91	2013-06-12T15.34.52.9391.n42
DU	None	U-238 (NORM)	97	2013-06-12T13.52.21.5490.n42

† The shielding thickness has an uncertainty of  $\pm 10\%$  ( $k=1$ )

**Table 9: Results of gamma and neutron readings, and radionuclides identified for BRD3 - Dynamic**

Source	Actual Shielding thickness (cm) †	Gamma Level*	Neutron Level*	Net Gamma reading (cps)	Net Neutron reading (cps)	Radionuclides Identified
Background	None	0 ± 0	0 ± 0	233 ± 6	3.7 ± 0.9	No ID (5)
HEU	None	5 ± 0	0 ± 0	178 ± 6	NA	U-235 HE (4), No ID (1)
HEU + Lead #1	0.0397	3 ± 0	0 ± 0	81.9 ± 2.4	NA	No ID (5)
HEU + Lead #2	0.0794	1.2 ± 0.5	0 ± 0	46.3 ± 1.1	NA	No ID (5)
HEU + Steel	0.4763	3.8 ± 0.5	0 ± 0	96.1 ± 2.1	NA	No ID (5)
HEU + HDPE	4.7142	4.4 ± 0.5	0 ± 0	134 ± 3	NA	No ID (5)
HEU + Steel+ HDPE	0.3175 Steel/ 2.5286 HDPE	4 ± 0	0 ± 0	95.3 ± 1.6	NA	No ID (5)
WGPu <sup>††</sup>	None	9 ± 0	0 ± 0	955 ± 57	NA	Am-241 (4), Ba-133 (1)
WGPu	None (with 5 mm copper)	6 ± 0	0.2 ± 0.5	219 ± 8	NA	Am-241 (1), No ID (4)
WGPu	None (with 4.5 mm steel)	7 ± 0	0 ± 0	337 ± 6	NA	Am-241 (4), No ID (1)
WGPu	None (with 8.2 mm steel)	6 ± 0	0 ± 0	211 ± 8	NA	RG Pu (1), No ID (4)
WGPu + Lead #1 <sup>††</sup>	0.2381	3 ± 0	0 ± 0	77 ± 3	NA	No ID (5)
WGPu + Lead #2 <sup>††</sup>	0.3175	3 ± 0	0 ± 0	72.9 ± 1.7	NA	Ba-133 (1), No ID (4)
WGPu + Steel <sup>††</sup>	0.9525	5 ± 0	0 ± 0	147 ± 6	NA	Co-57 (1), No ID (4)
WGPu + HDPE <sup>††</sup>	7.9794	9 ± 0	0 ± 0	664 ± 43	NA	No ID (5)
WGPu + Steel <sup>††</sup> HDPE	0.4763 Steel/ 3.7833 HDPE	5.8 ± 0.5	0 ± 0	194 ± 5	NA	No ID (5)
DU	None	6 ± 0	0 ± 0	261 ± 8	NA	No ID (5)
Uncertainties have a coverage factor, k, of 1 † The shielding thickness has an uncertainty of ± 10 % (k=1) ††The WGPu was surrounded by 3 sheets of gauge 28 galvanized metal * The ranges of the levels are 0 to 9						

## 6. Recommendations

Based on the present validation measurements the following should be considered:

- The copper, steel or cadmium shielding used to reduce the  $^{241}\text{Am}$  present in the WGPu source shall be used for all bare and shielded test configurations. The testing distance and speed for WGPu shall be calculated based on the shielded source with the reduced  $^{241}\text{Am}$  emission.
- The shielding thicknesses that can be purchased without alteration of the material do not produce a 50 % reduction in emission rate. The purchased shielding thicknesses produce attenuation factors that vary between 0.40 and 0.58. Therefore, the purchased material without alteration could be used for the measurements if the standard specifies that the attenuation factor can range between 0.40 and 0.60.
- From the four commercially available lead thicknesses, it is suggested to use the 0.04 cm (1/64 inch) for HEU and 0.24 cm (3/32 inch) for the WGPu sources. These provide an attenuation factor closer to 0.5.
- It is recommended that the steel and HDPE shielding be made in a cylindrical shape. Welding the material into boxes or removing material from a solid cylinder has a similar cost.
- Two out of the three BRDs didn't have any issues in detecting the sources. Therefore, the fluence rates specified in the standard can be reduced and still be detectable by these BRDs.
- A track or linear motion system will be required to provide an adjustable testing speed.
- The BRD and source height of 1.5 m from the floor represents very tall users. Suggest reducing the testing height to 1.3 m from the floor to represent average height users.
- Due to possible presence of large amounts of  $^{241}\text{Am}$  in the WGPu source, it will be necessary to have the WGPu source be placed inside a copper, steel or cadmium shielding to reduce  $^{241}\text{Am}$  contribution to the required levels. This new shielded source configuration (i.e., WGPu plus copper, steel or cadmium) shall be considered the bare source and it shall then be used to calculate the fluence rate and testing distance for all the test configurations.
- When the WGPu source was shielded with lead (both thicknesses) the  $^{241}\text{Am}$  peak at 59.54 keV was not observed in the spectrum. For all other shielding types, the  $^{241}\text{Am}$  peak was clearly visible.
- The BRD2 was automatically updating background when the WGPu was placed at the required testing distance of 47cm due to the large  $^{241}\text{Am}$  signal.