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Assessment of PHDS Fulcrum40h and Ortec Detective-X High Purity Germanium (HPGe) Detector System Performance

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ABSTRACT

This report provides a summary of measurement results used to compare the performance of the PHDS Fulcrum40h and Ortec Detective-X High Purity Germanium (HPGe) detector systems.

Specifically, the measurement data collected was used to assess each detector system for gamma efficiency and resolution, gamma angular response and efficiency for an in-situ surface distribution, neutron efficiency, gamma pulse-pileup response, and gamma to neutron crosstalk.

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ACRONYMS AND TERMS

Acronym/Term	Definition
BPE	Borated Polyethylene
FWHM	Full Width at Half Maximum
GADRAS	Gamma Detector Response and Analysis Software
HPGe	High Purity Germanium
MCA	Multichannel Analyzer
PE	Polyethylene

1. OVERVIEW

This report provides a summary of measurement results used to compare the performance of the PHDS Fulcrum40h and Ortec Detective-X High Purity Germanium (HPGe) detector systems (Figure 1 and Table 1).

Figure 1. PHDS Fulcrum40h (left) and Ortec Detective-X (right).

Table 1. General detector system specifications.

Description	PHDS Fulcrum40h	Ortec Detective X
HPGe dimensions	80-mm diameter x 30-mm deep, p-type HPGe, Coaxial construction	65-mm diameter x 50-mm deep, p-type HPGe, Coaxial construction
Relative efficiency	≈ 40% relative efficiency	≈ 40% relative efficiency
Energy range	3 MeV (≈24,000 channels or ≈0.125 keV/channel)	8 MeV (16,384 channels or ≈0.488 keV/channel)
Neutron detector	Utilizes microstructured semiconductor neutron detector (MSND®) technology with 6Li(n,t)4He reaction. Detector surface area is 4 cm2 and is up to 30% efficient at detecting thermal neutrons.	Large volume segmented Li6F/ZnS detector formed in a U-shape that sits behind the HPGe detector.

Note: Relative efficiency is the efficiency of the detector at 1332.5 keV to that of a 3-inch x 3-inch NaI gamma-radiation detector at 25-cm from the detector endcap which is quoted as 1.2 x 10-3 counts per gamma for a point source. Therefore, relative efficiency values greater than 100% can be encountered when working with large or very large germanium detectors.

Measurement data was collected to assess each detector system for gamma efficiency and resolution, gamma angular response and efficiency for an in-situ surface distribution, neutron efficiency, gamma pulse-pileup response, and gamma to neutron crosstalk. The data collected was also used to generate Gamma Detector Response and Analysis Software (GADRAS) detector response functions (gamma and neutron) and efficiencies for in-situ gamma spectroscopy analysis.

Gamma efficiency and resolution were assessed using 6 Fulcrum40h and 6 Detective-X detector systems while gamma angular response and efficiency for an in-situ surface distribution, neutron

efficiency, gamma pulse-pileup response, and gamma to neutron crosstalk were assessed using 1 Fulcrum40h (FF105) and 1 Detective-X (21180856) detector system. Fulcrum40h (FF105) and Detective-X (21180856) were selected as reasonable representations of average Fulcrum40h and Detective-X detector system performance. An efficiency comparison of the Fulcrum40h (FF105) and Detective-X (21180856) compared to the average of the 6 Fulcrum40h and 6 Detective-X detector system efficiencies, respectively, is provided in Section **Error! Reference source not found.**.

For this assessment, the Fulcrum40h detector systems used were brand new (≈August 2022) while the Detective-X detector systems were manufactured between May 28, 2020 and August 29, 2022 (see Appendix A). Ideally, a direct comparison of brand new detectors for both the Fulcrum40h and Detective-X detector systems would have been best but was not feasible. Lastly, the measurement plan as executed is provided in Appendix B.

1.1. Fulcrum40h (FF105) and Detective-X (21180856) gamma efficiencies compared to average

Due to time and cost constraints, 1 Fulcrum40h (FF105) and 1 Detective-X (21180856) detector system were used for gamma in-situ surface distribution angular response and efficiency, gamma pulse-pileup response, neutron efficiency, and gamma to neutron crosstalk comparisons.

Their efficiencies at 100-cm relative to the average Fulcrum40h and Detective-X efficiencies are provided in Table 2.

Table 2. Gamma efficiency of Fulcrum40h (FF105) and Detective-X (21180856) compared to average gamma Fulcrum40h and Detective-X efficiencies.

			FF105		DetX-0856	
Nuclide	Energy (keV)	Yield (gps/dps)	Efficiency (c/g)	FF105 / Fulcrum Avg	Efficiency (c/g)	DetX-0856 / DetX Avg
Am-241	59.5	3.59E-01	1.62E-04	96%	7.34E-05	84%
Ba-133	80.9	3.67E-01	2.20E-04	98%	1.28E-04	90%
Ba-133	160.6	6.45E-03	2.50E-04	94%	1.83E-04	104%
U-232+	238.8	4.74E-01	1.96E-04	99%	1.46E-04	102%
U-232+	277.4	2.27E-02	1.79E-04	99%	1.33E-04	96%
U-232+	300.1	3.28E-02	1.58E-04	98%	1.19E-04	93%
Ba-133	302.9	1.83E-01	1.51E-04	99%	1.21E-04	98%
Ba-133	356.0	6.21E-01	1.28E-04	98%	1.08E-04	98%
Ba-133	383.8	8.94E-02	1.21E-04	101%	1.00E-04	98%
U-232+	583.2	3.04E-01	8.16E-05	98%	7.62E-05	100%
Cs-137	661.7	8.47E-01	7.26E-05	101%	6.65E-05	99%
U-232+	727.3	6.58E-02	6.78E-05	100%	6.28E-05	96%
U-232+	860.6	4.47E-02	5.99E-05	102%	5.87E-05	102%
Co-60	1173.2	9.99E-01	4.21E-05	99%	4.24E-05	100%
Co-60	1332.5	1.00E+00	3.80E-05	100%	3.81E-05	98%
U-232+	1620.5	1.49E-02	3.20E-05	95%	3.71E-05	109%
U-232+	2614.5	3.56E-01	2.07E-05	101%	2.30E-05	100%

Ba-133 81.0 keV (Yield = 34.1%) and 79.6 keV (Yield = 2.62%) peaks were combined.
U-232+ 238.6 keV (Yield = 43.3%) and 241.0 keV (Yield = 4.1%) peaks were combined.

As shown, the Fulcrum40h (FF105) represents the average Fulcrum40h detector system efficiency from 59.5 to 2614.5 keV very well (within 5%) and the Detective-X (21180856) represents the average Detective-X detector system efficiency well (within 10% from 80.9 to 2614.5 keV). Only the Detective-X (21180856) efficiency at 59.5 keV is more than 10% different than the average Detective-X detector system efficiency (calculated at 84% of the average). Accordingly, the Detective-X (21180856) detector system results presented will underestimate the efficiency of the average Detective-X at 59.5 keV by roughly 15%.

1.2. Average gamma efficiency comparison

The following provides a comparison of the average gamma efficiency for 6 Fulcrum40h and 6 Detective-X detector systems based on Am-241, Ba-133, Cs-137, Co-60, and U-232 point source measurements at 100-cm from the detector face. The measurements used the same sources in the same measurement configuration and scatter environment.

As shown in Table 3, individual Fulcrum40h and Detective-X efficiencies were reasonably consistent compared to the average efficiency below 200 keV with the Detective-X efficiency being more variable below 100 keV. The variability of the Detective-X efficiencies below 100 keV is potentially due the detector systems not being brand new and experiencing dead layer growth over time. Therefore, this evaluation may underestimate the efficiency of brand new Detective-X detector systems below ≈100 keV.

Note: Dead layer growth increases when the detector is not maintained at cryogenic temperatures (aka, when the detector is at room or elevated temperatures). Unfortunately, the use and temperature history of the Detective-X detector systems was not known.

Table 3. Average gamma efficiency comparison.

			Fulcrum40			DetX			
Nuclide	Energy (keV)	Yield (gps/dps)	Peak Area cps	Efficiency (c/g)	Efficiency Std Dev (%)	Peak Area cps	Efficiency (c/g)	Efficiency Std Dev (%)	Fulcrum40 / DetX
Am-241	59.5	3.59E-01	234.5	1.68E-04	5.1%	122.6	8.78E-05	33.3%	191%
Ba-133	80.9	3.67E-01	257.6	2.23E-04	3.4%	163.1	1.41E-04	15.5%	158%
Ba-133	160.6	6.45E-03	5.4	2.67E-04	10.0%	3.5	1.75E-04	11.5%	153%
U-232+	238.8	4.74E-01	301.1	1.98E-04	1.2%	218.6	1.43E-04	10.9%	138%
U-232+	277.4	2.27E-02	13.2	1.81E-04	4.7%	10.1	1.38E-04	5.4%	131%
U-232+	300.1	3.28E-02	16.9	1.61E-04	2.3%	13.5	1.28E-04	5.5%	126%
Ba-133	302.9	1.83E-01	87.7	1.52E-04	1.8%	71.4	1.24E-04	4.4%	123%
Ba-133	356.0	6.21E-01	253.8	1.30E-04	1.6%	213.9	1.10E-04	3.7%	119%
Ba-133	383.8	8.94E-02	33.6	1.19E-04	1.3%	28.8	1.02E-04	4.9%	117%
U-232+	583.2	3.04E-01	81.1	8.31E-05	2.4%	74.2	7.60E-05	5.3%	109%
Cs-137	661.7	8.47E-01	161.4	7.20E-05	1.7%	150.6	6.72E-05	3.8%	107%
U-232+	727.3	6.58E-02	14.3	6.77E-05	2.8%	13.8	6.51E-05	4.5%	104%
U-232+	860.6	4.47E-02	8.4	5.88E-05	3.7%	8.2	5.73E-05	5.2%	103%
Co-60	1173.2	9.99E-01	92.3	4.26E-05	1.8%	91.6	4.23E-05	4.3%	101%
Co-60	1332.5	1.00E+00	82.2	3.79E-05	2.9%	84.2	3.89E-05	4.2%	98%
U-232+	1620.5	1.49E-02	1.6	3.35E-05	7.9%	1.6	3.41E-05	8.1%	98%
U-232+	2614.5	3.56E-01	23.6	2.06E-05	2.9%	26.2	2.29E-05	4.4%	90%

Ba-133 81.0 keV (Yield = 34.1%) and 79.6 keV (Yield = 2.62%) peaks were combined.
U-232+ 238.6 keV (Yield = 43.3%) and 241.0 keV (Yield = 4.1%) peaks were combined.

As shown in Figure 2, the average Fulcrum40h efficiency below roughly 600 keV is better than the average Detective-X efficiency due to its larger diameter (80-mm versus 65-mm). At energies above roughly 2000 keV, the average Detective-X efficiency is better than the average Fulcrum40h efficiency due to its larger crystal depth (50-mm versus 30-mm). Although not measured, the Detective-X efficiency advantage relative to the Fulcrum40h will increase with energies above 2614.5 keV due to its larger crystal depth.

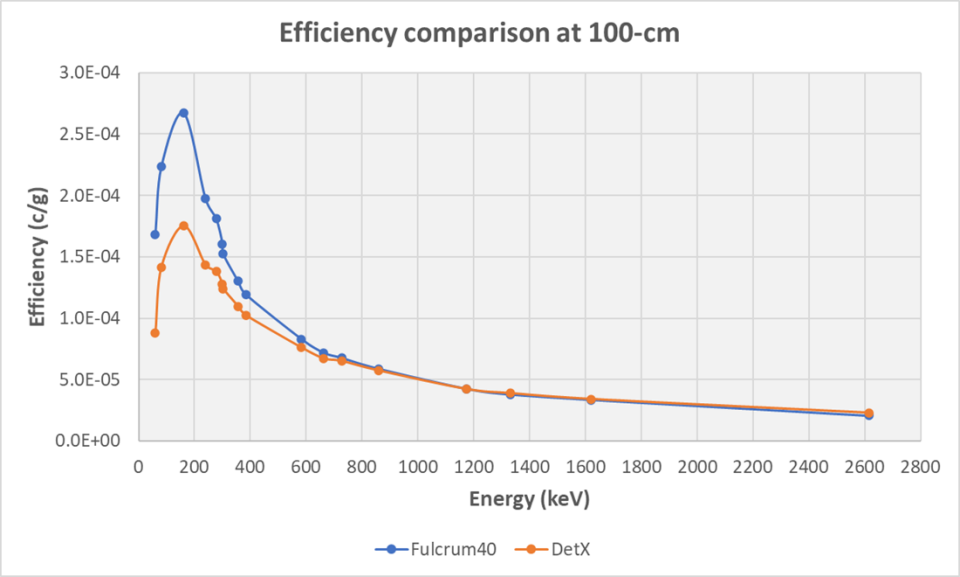

Figure 2. Average gamma efficiency comparison at 100-cm.

1.3. Average gamma resolution comparison

The following provides a comparison of the average gamma resolution for 6 Fulcrum40h and 6 Detective-X detector systems based on Am-241, Ba-133, Cs-137, Co-60, and U-232 point source measurements at 100-cm from the detector face. The measurements used the same sources in the same measurement configuration and scatter environment.

As shown in Figure 3, the average Fulcrum40h and the Detective-X resolution as a function of energy are reasonably close with a small advantage to the Fulcrum40h at lower energies and Detective-X at higher energies. The resolution assessment was performed using the default factory Fulcrum40h and Detective-X energy scales of ≈0.125 keV/channel and ≈0.488 keV/channel, respectively.

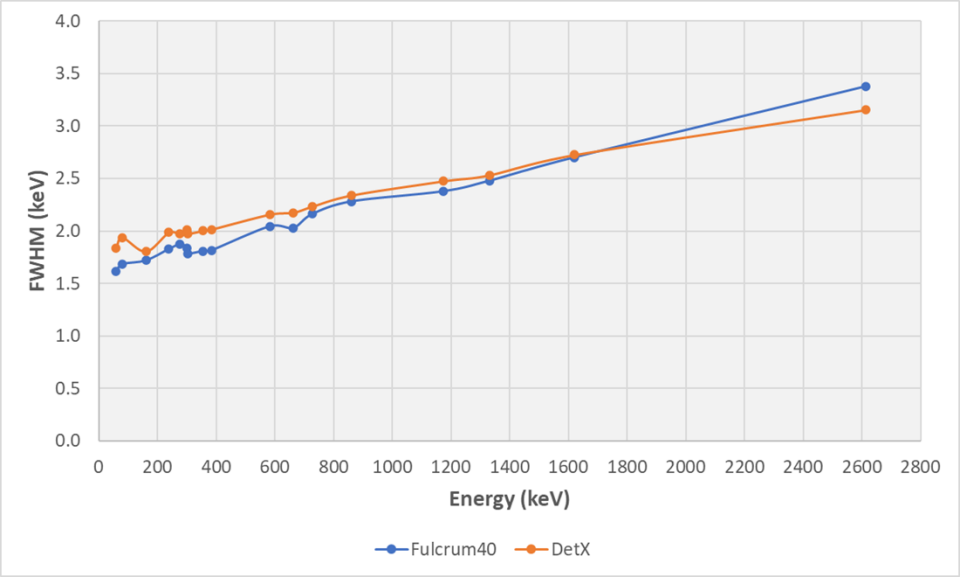

Figure 3. Average gamma resolution comparison.

Accordingly, the small advantage of the Fulcrum40h at lower energies may be due to the Detective-X not using the optimum number of channels. Assuming a Detective-X resolution of 1.6 keV at ≈200 keV and using the guideline of setting the spectrum size equal to 4 channels per full width at half maximum (FWHM), an optimum energy scale of 0.400 keV/channel would be calculated which is below the coarser 0.488 keV/channel used by Ortec [1]. Accordingly, the Detective-X resolution may actually be better at lower energies than indicated by the measurements due to the multichannel analyzer (MCA) having an insufficient number of channels for the 8 MeV range.

1.4. In-situ surface distribution angular response and efficiency comparison

The following provides an in-situ surface distribution angular response and efficiency comparison of 1 Fulcrum40h (FF105) and 1 Detective-X (21180856) detector system. The in-situ calibration measurements included characterization of the angular response at 0, 15, 30, 45, 60, 75, and 90 degrees using Am-241, Ba-133, Cs-137, Co-60, and U-232 point source measurements at 100-cm from the detector face. The measurements used the same sources in the same measurement configuration and scatter environment.

Figure 4. Fulcrum40h in-situ angular response measurement in progress.

As shown in Table 4 and Figure 5, the Fulcrum40h (FF105) in-situ surface distribution efficiency below 100 keV is significantly better than the Detective-X (21180856). Above 100 keV, the Detective-X (21180856) in-situ surface distribution efficiency exceeds the Fulcrum40h (FF105).

Note: As stated in Sections **Error! Reference source not found.** and **Error! Reference source not found.**, Detective-X (21180856) detector system results will underestimate the efficiency of the average Detective-X and this evaluation may underestimate the efficiency of brand new Detective-X detector systems below ≈100 keV.

The differences observed are largely due to the in-situ surface distribution field of view increasing with energy. As the field of view increases, the fraction of the fluence rate hitting the side of the detector increases. Although the Fulcrum40h has a larger diameter (80-mm versus 65-mm) which benefits it below 100 keV, it is not as tall as the Detective-X (30-mm versus 50-mm) resulting in lower in-situ surface distribution efficiencies at higher energies when compared to the Detective-X.

Table 4. In-situ surface distribution efficiency and angular correction factor comparison.

	Fulcrum40_FF105			DetX_RAP4-0856		
Energy (keV)	No / Φ cps / (g/cm2*s)	Nf / No unitless	Nf / A (cps) / (Bq/cm2)	No / Φ cps / (g/cm2*s)	Nf / No unitless	Nf / A (cps) / (Bq/cm2)
59.5	20.19	0.52	17.29	8.84	0.53	7.71
70.0	25.16	0.59	24.88	13.27	0.66	14.58
80.0	28.74	0.60	29.19	16.70	0.73	20.71
90.0	31.25	0.59	31.41	19.22	0.78	25.56
100.0	32.84	0.57	32.37	20.92	0.80	29.03
125.0	33.98	0.54	32.40	22.65	0.83	33.18
150.0	32.79	0.54	31.45	22.41	0.85	33.74
175.0	30.66	0.55	30.36	21.41	0.85	32.90
200.0	28.27	0.57	29.28	20.17	0.86	31.58
250.0	23.77	0.61	27.16	17.75	0.87	28.82
300.0	20.11	0.66	25.02	15.72	0.89	26.36
400.0	15.06	0.71	20.95	12.75	0.91	22.51
500.0	11.96	0.74	17.56	10.77	0.92	19.66
600.0	9.95	0.74	14.99	9.36	0.92	17.49
700.0	8.56	0.74	13.12	8.32	0.92	15.81
800.0	7.56	0.74	11.79	7.51	0.92	14.50
900.0	6.81	0.75	10.85	6.86	0.92	13.45
1000.0	6.22	0.76	10.20	6.33	0.93	12.59
1200.0	5.35	0.80	9.42	5.51	0.94	11.31
1400.0	4.72	0.86	9.03	4.89	0.95	10.38
1600.0	4.23	0.91	8.75	4.40	0.97	9.66
1800.0	3.83	0.96	8.43	4.00	0.98	9.05
2000.0	3.48	0.98	7.95	3.67	1.00	8.50
2400.0	2.89	0.93	6.38	3.12	1.00	7.39

Nf / A = (No / Φ) • (Nf / No) • (Φ / A)

- Nf / A = Detector full energy peak count rate per unit concentration for a surface source distribution
- Φ / A = Uncollided gamma fluence rate (flux) at the detector face per unit concentration for a surface source distribution
- No / Φ = Detector full energy peak efficiency at normal incidence
- Nf / No = Detector full energy peak efficiency angular correction factor for a surface source distribution

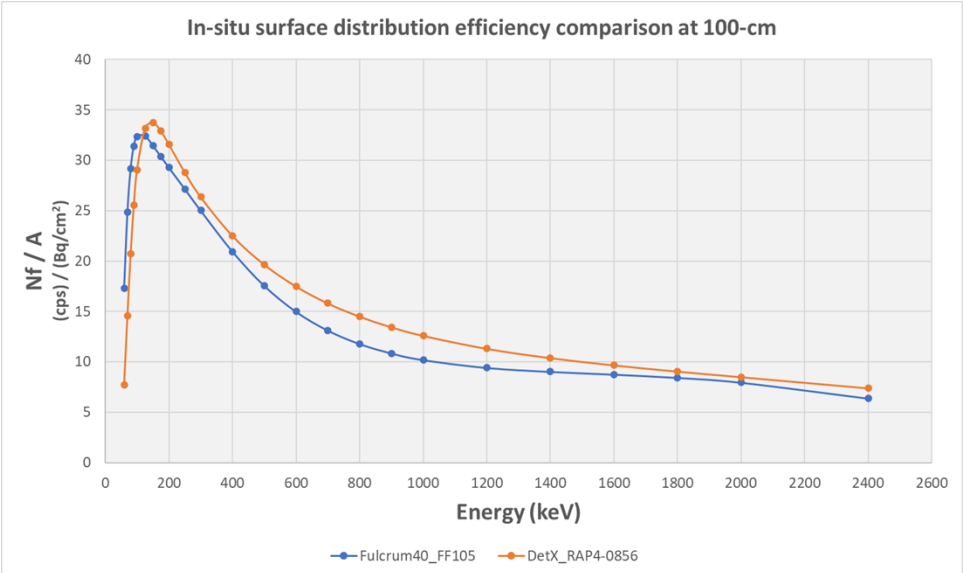

Figure 5. In-situ surface distribution efficiency comparison.

1.5. Neutron efficiency comparison

The following provides a comparison of the neutron efficiency for 1 Fulcrum40h (FF105) and 1 Detective-X (21180856) detector system based on Cf-252 point source measurements at 100-cm from the detector face. As shown in Table 5, the Cf-252 point source measurements included measurements of the Cf-252 source inside polyethylene (PE) and borated polyethylene (BPE) spheres of various inside (ID) and outside diameters (OD).

Table 5. Cf-252 measurement configurations.

Configurations
Cf-252 bare
Cf-252 inside 4-cm PE sphere (OD = 14-cm, ID = 6-cm)
Cf-252 inside 8-cm Borated PE sphere (OD = 20-cm, ID = 4-cm)
Cf-252 inside 2-cm PE sphere (OD = 14-cm, ID = 10-cm)
Cf-252 inside 8-cm PE sphere (OD = 20-cm, ID = 4-cm)
Cf-252 inside 4-cm PE sphere (OD = 14-cm, ID = 6-cm) at 90 degrees

Figure 6. Fulcrum40h neutron efficiency measurement in progress.

As shown in Table 6 and Figure 7, the Detective-X (21180856) neutron efficiency is roughly 20 to 50 times better (dependent on the Cf-252 moderation configuration) than the Fulcrum40h (FF105). This is expected due to the much larger surface area/volume of the Detective-X neutron detector as compared to the Fulcrum40h detector.

Table 6. Neutron efficiency comparison.

Measurement Description	Fulcrum40_FF105 Eff (c/n)	DetX_RAP4-0856 Eff (c/n)	DetX_RAP4-0856 / Fulcrum40_FF105
Bare	1.60E-06	3.69E-05	23.1
2-cm PE	2.60E-06	8.08E-05	31.1
4-cm PE	3.91E-06	1.23E-04	31.5
8-cm PE	3.23E-06	1.23E-04	38.3
8-cm BPE	1.88E-06	5.35E-05	28.4
4-cm PE at 90 degrees	1.95E-06	9.97E-05	51.3

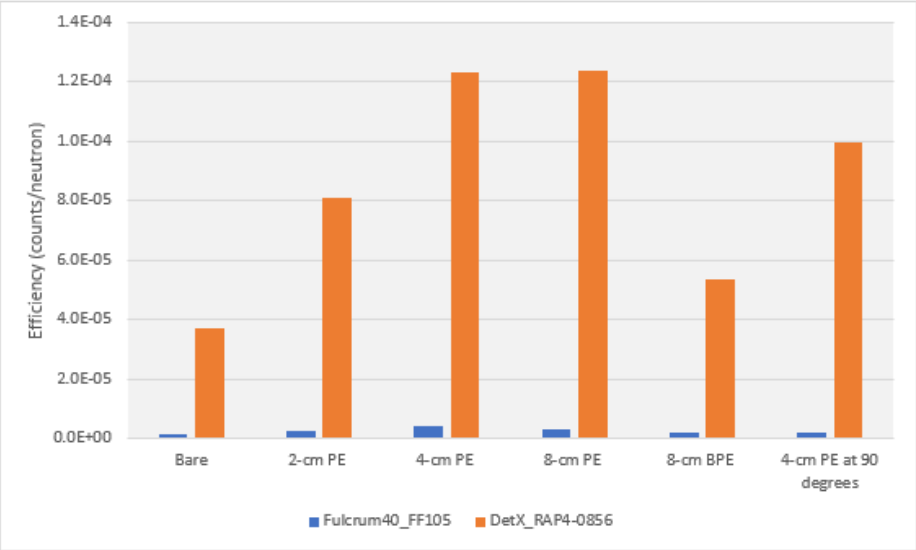

Figure 7. Neutron efficiency comparison.

1.6. Gamma pulse-pileup response: U-232 and Cs-137

The following provides a comparison of the gamma pulse-pileup response for 1 Fulcrum40h (FF105) and 1 Detective-X (21180856) detector system using U-232 and Cs-137 sources.

Pulse-pileup response measurements were performed to evaluate pile up rejection/live time correction performance, resolution as a function of total gamma count rate, and gamma to neutron cross talk as a function of total gamma count rate.

Using a U-232 sealed source of moderate activity, a measurement was conducted with minimal dead time to establish reference 583.2 and 2614.5 keV full energy peak count rates. Without moving the U-232 sealed source, subsequent measurements were conducted by adding a Cs-137 sealed source at various distances to generate count rates ranging between roughly 200 cps and 37,000 cps on both detector systems. The measured 583.2 and 2614.5 keV peak count rates of U-232 were then used to evaluate the accuracy of pulse-pileup correction as a function of count rate/dead time.

Pulse-pileup correction factor = Measured peak count rate divided by reference peak count rate (aka peak count rate measured at minimal dead time).

1.6.1. Pile up rejection/live time correction performance

Pile up rejection/live time correction performance results for Fulcrum40h (FF105) and Detective-X (21180856) detector systems are provided in Table 7, Table 8, Figure 8, and Figure 9.

Note: A 5% 3-sigma systematic error was assumed and propagated with peak area uncertainties to derive the pulse pileup correction factors.

Table 7. Fulcrum40h (FF105) pulse-pileup response.

Nuclides	Dead Time (%)	Gamma (cps)	583.2 keV CF ± 1.96-Sigma	2614.5 keV CF ± 1.96-Sigma
U-232 alone	1.2%	1051	1.000 ± 0.044	1.000 ± 0.064
U-232 + Cs137	3.2%	3505	0.980 ± 0.045	0.929 ± 0.065
U-232 + Cs137	4.9%	5473	0.946 ± 0.046	0.947 ± 0.065
U-232 + Cs137	10.0%	11482	0.914 ± 0.050	0.995 ± 0.066
U-232 + Cs137	14.6%	17144	0.878 ± 0.054	0.917 ± 0.067
U-232 + Cs137	19.7%	23778	0.835 ± 0.061	0.912 ± 0.068
U-232 + Cs137	24.3%	30049	0.810 ± 0.061	0.852 ± 0.065
U-232 + Cs137	29.1%	36928	0.758 ± 0.077	0.798 ± 0.072
Background	1.1%	215	---	---

Gamma (cps) = Total gamma count rate (cps) in the entire spectrum.

Table 8. Detective-X (21180856) pulse-pileup response.

Nuclides	Dead Time (%)	Gamma (cps)	583.2 keV CF ± 1.96-Sigma	2614.5 keV CF ± 1.96-Sigma
U-232 alone	3.8%	1132	1.000 ± 0.040	1.000 ± 0.051
U-232 + Cs137	5.9%	1759	0.980 ± 0.042	0.974 ± 0.054
U-232 + Cs137	11.0%	3376	0.958 ± 0.042	1.005 ± 0.054
U-232 + Cs137	18.2%	5833	0.956 ± 0.043	0.931 ± 0.055
U-232 + Cs137	31.0%	10862	0.950 ± 0.046	0.989 ± 0.058
U-232 + Cs137	38.8%	14436	0.984 ± 0.048	1.034 ± 0.058
U-232 + Cs137	48.9%	19892	0.959 ± 0.051	0.961 ± 0.061
U-232 + Cs137	59.7%	27266	0.914 ± 0.061	1.046 ± 0.065
U-232 + Cs137	69.3%	35945	0.923 ± 0.070	0.944 ± 0.072
Background	0.8%	219	---	---

Gamma (cps) = Total gamma cps in the entire spectrum.

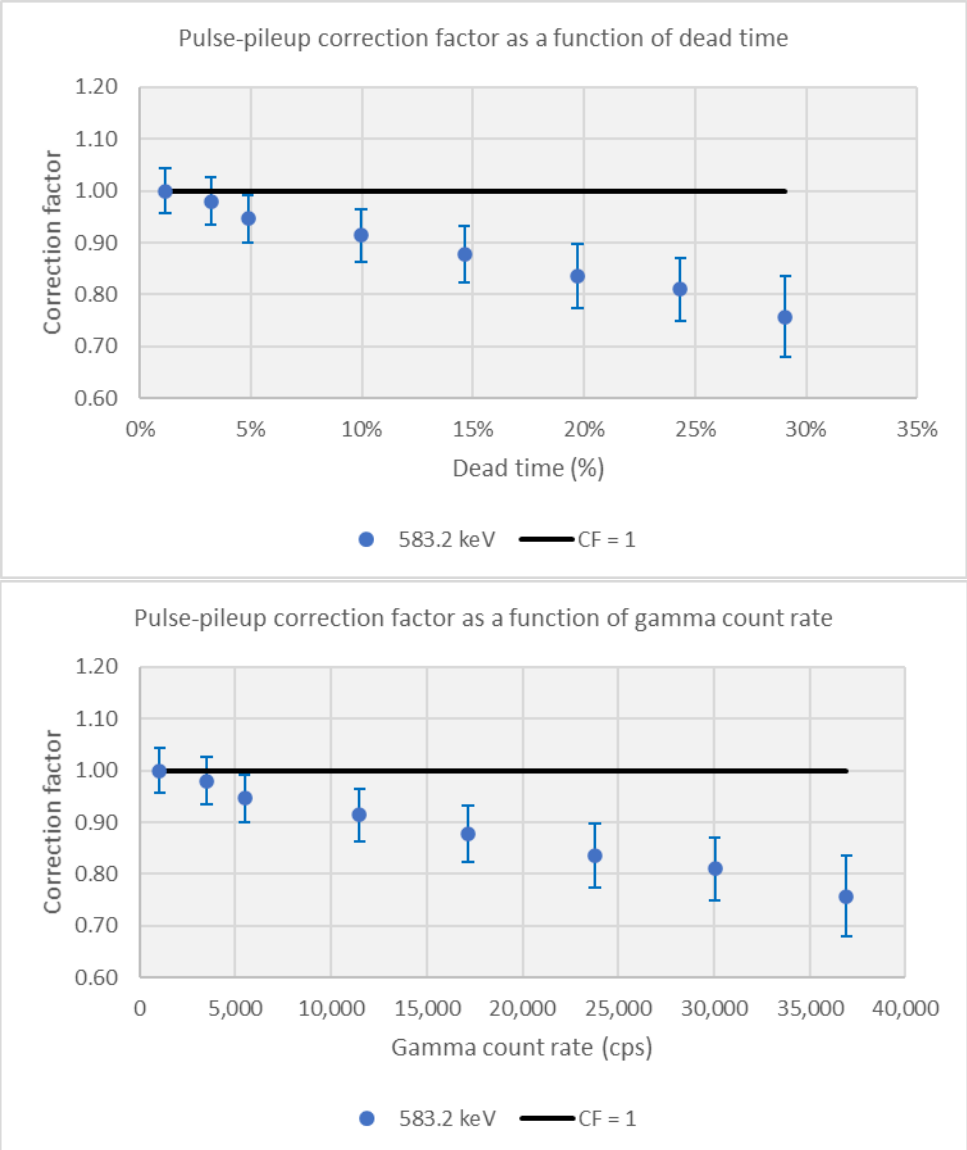

Figure 8. Fulcrum40h (FF105) pulse-pileup correction factor at 583.2 keV as a function of dead time and gamma count rate.

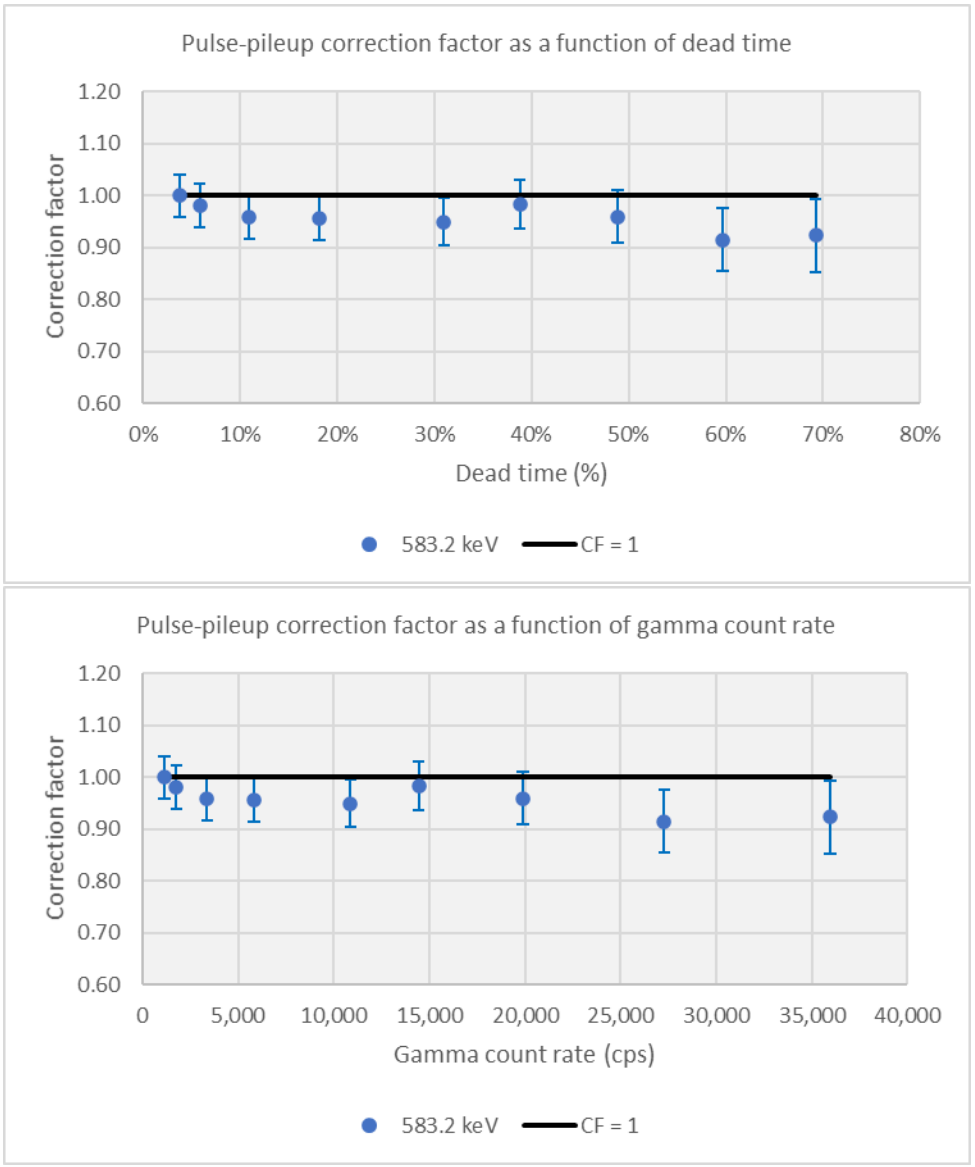

Figure 9. Detective-X (21180856) pulse-pileup correction factor at 583.2 keV as a function of dead time and gamma count rate.

For the Fulcrum40h (FF105) detector system, the results indicate that the pulse-pileup correction is accurate within 10% at count rates up to ≈11,500 cps (≈10% dead time). As count rates increase, the Fulcrum40h (FF105) detector system inaccuracy increases and underestimates the peak areas by 20 to 25% at ≈37,000 cps (≈30% dead time). In comparison, the results indicate that the pulse-pileup correction for Detective-X (21180856) detector system is accurate within 10% at count rates up to ≈36,000 cps (≈70% dead time).

1.6.2. Resolution as a function of total gamma count rate

Resolution as a function of total gamma count rate and dead time for the Fulcrum40h (FF105) and Detective-X (21180856) detector systems are provided in Figure 10 and Figure 11. In addition, spectra of the 2614.5 keV peak resolution measured at minimal dead time and high dead time are presented in Figure 12 and Figure 13.

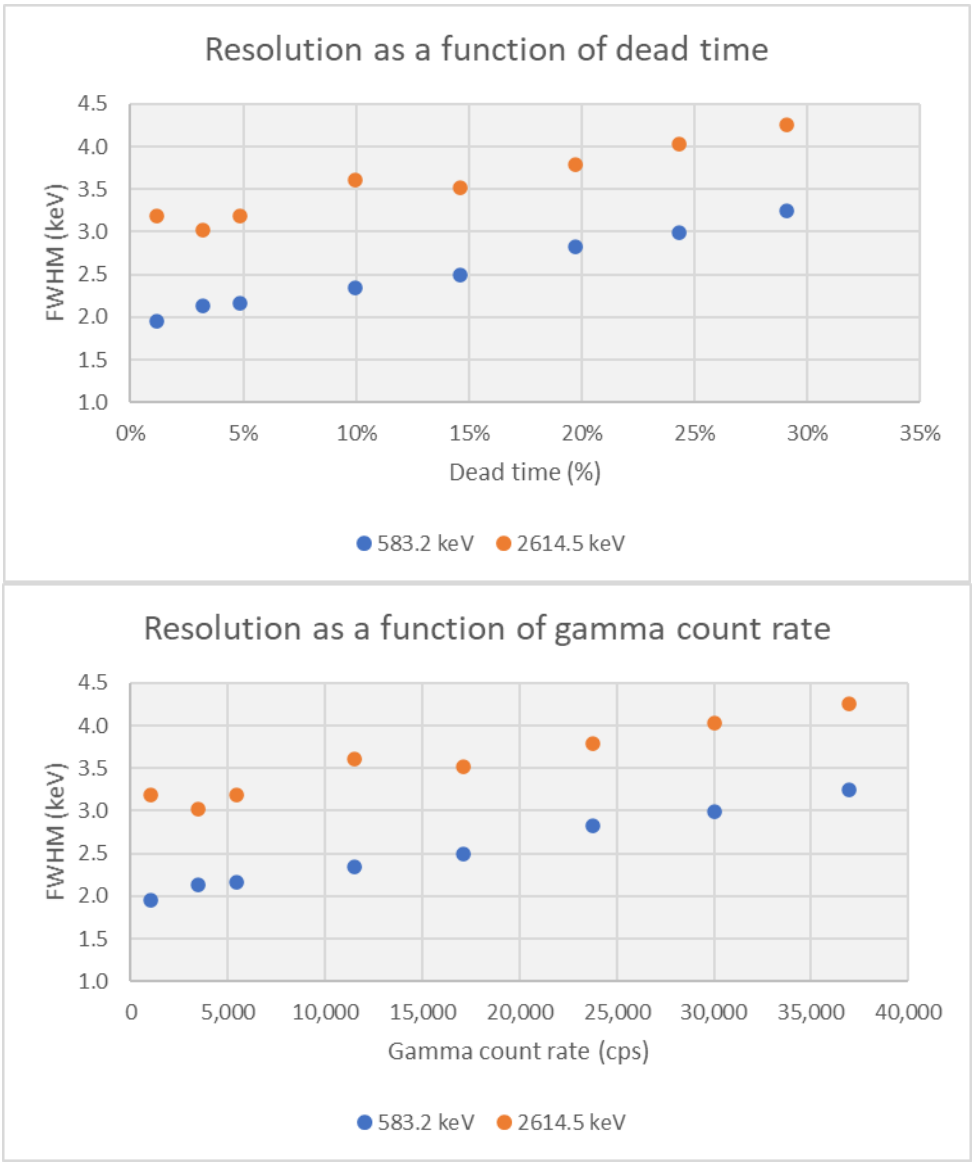

Figure 10. Fulcrum40h (FF105) resolution as a function of dead time and gamma count rate.

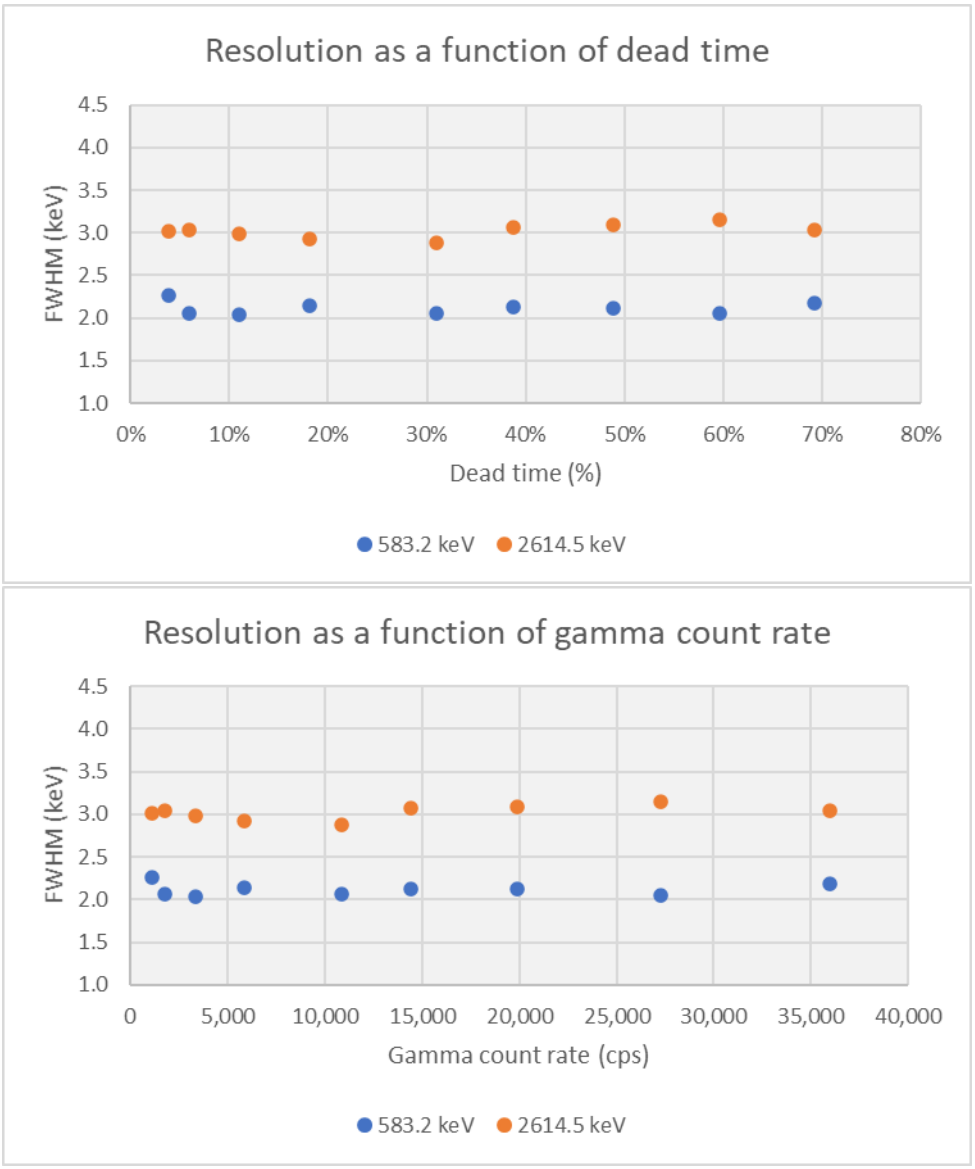

Figure 11. Detective-X (21180856) resolution as a function of dead time and gamma count rate.

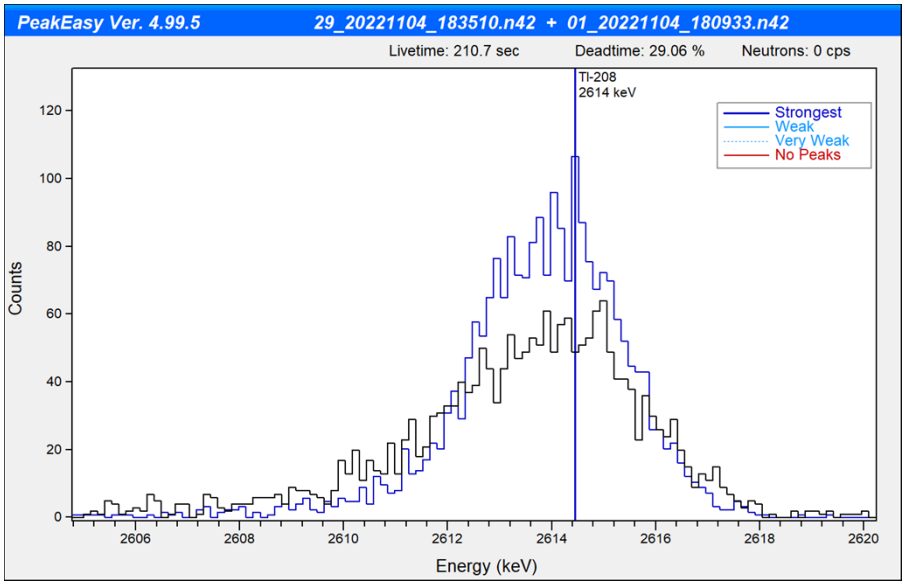

Figure 12. Fulcrum40h (FF105) 2614.5 keV peak resolution measured at minimal dead time (blue) and ≈30% dead time ≈37,000 cps (black). Linear scale.

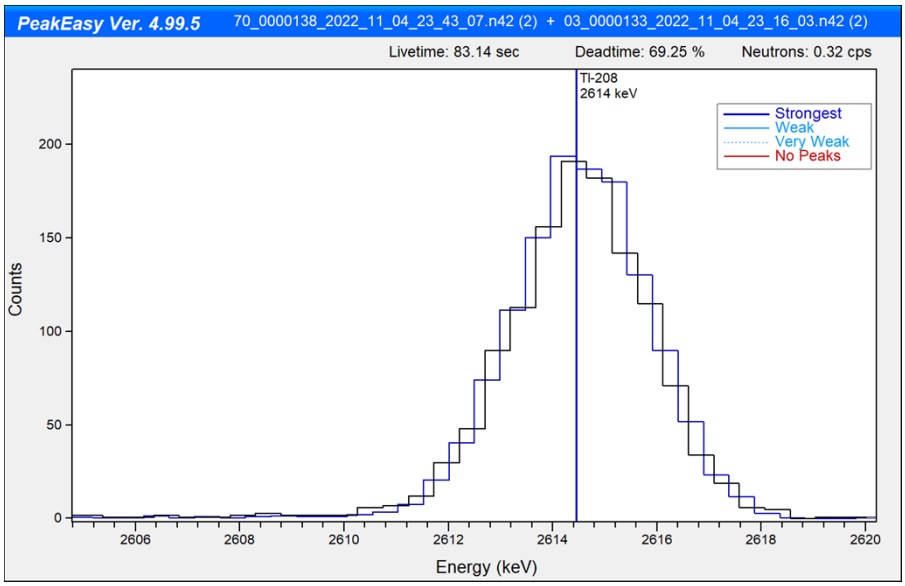

Figure 13. Detective-X (21180856) 2614.5 keV peak resolution measured at minimal dead time (blue) and ≈70% dead time ≈36,000 cps (black). Linear scale.

Similar to the pile up rejection/live time correction performance results, the Fulcrum40h (FF105) detector system resolution degrades as a function of total gamma count rate beginning roughly at ≈11,500 cps (≈10% dead time). In contrast, the Detective-X (21180856) detector system shows no noticeable degradation in resolution as a function of total gamma count rate.

1.6.3. Gamma to neutron cross talk as a function of total gamma count rate

Results for gamma to neutron cross talk as a function of total gamma count rate for the Fulcrum40h (FF105) detector system are provided in Table 9.

Table 9. Fulcrum40h (FF105) gamma to neutron cross talk as a function of gamma count rate.

Nuclides	Dead Time (%)	Live Time (sec)	Real Time (sec)	Gamma (cps)	Neutron (counts)	Neutron (cps)	Net (cps)	Critical Level Net (cps)
Background	1.1%	885.4	895.0	215	13	0.0147	---	---
U-232 alone	1.1%	259.0	262.0	1051	2	0.0077	-0.0070	0.0166
U-232 + Cs137	3.2%	260.4	269.0	3505	1	0.0038	-0.0108	0.0165
U-232 + Cs137	4.9%	239.7	252.0	5473	2	0.0083	-0.0064	0.0171
U-232 + Cs137	10.0%	215.2	239.0	11482	2	0.0093	-0.0054	0.0179
U-232 + Cs137	14.6%	223.7	262.0	17144	1	0.0045	-0.0102	0.0176
U-232 + Cs137	19.7%	212.0	264.0	23778	5	0.0236	0.0089	0.0180
U-232 + Cs137	24.3%	289.8	383.0	30049	11	0.0380	0.0233	0.0159
U-232 + Cs137	29.1%	210.7	297.0	36928	0	0.0000	-0.0147	0.0180
Co-60	22.7%	234.9	304.0	27982	1	0.0043	-0.0104	0.0172

Critical level determined suing a one sided 95% confidence interval.

Due to the low neutron efficiency of the Fulcrum40h and corresponding low measured neutron counts, the net neutron count rate above background was compared to the critical level determined using the Stapleton approximation for the Poisson distribution to conclude whether a sample result was above background [2]. In one instance (U-232 + Cs-137 at a dead time of 24.3%), the net neutron count rate slightly exceeded the critical level. In all other instances, the net neutron count rate did not exceed the critical level. Overall, the Fulcrum40h results indicate that gamma radiation does not have an effect on the reported neutron detector count rate.

Similarly, results for gamma to neutron cross talk as a function of total gamma count rate for the Detective-X (21180856) detector system are provided in Table 10.

Table 10. Detective-X (21180856) gamma to neutron cross talk as a function of gamma count rate.

Nuclides	Dead Time (%)	Live Time (sec)	Real Time (sec)	Gamma (cps)	Neutron (counts)	Neutron (cps)	Two-Sided 90.0% CI (cps)
Background	0.76%	893.7	900.5	219	328	0.3642	---
U-232 alone	3.83%	320.5	333.3	1132	129	0.3870	(-0.042,0.088)
U-232 + Cs137	5.89%	241.3	256.4	1759	107	0.4174	(-0.021,0.127)
U-232 + Cs137	10.99%	226.4	254.3	3376	106	0.4168	(-0.022,0.127)
U-232 + Cs137	18.18%	246.4	301.2	5833	121	0.4017	(-0.031,0.106)
U-232 + Cs137	31.02%	175.2	253.9	10862	96	0.3780	(-0.058,0.085)
U-232 + Cs137	38.80%	162.4	265.3	14436	115	0.4334	(-0.005,0.143)
U-232 + Cs137	48.89%	141.4	276.7	19892	99	0.3578	(-0.074,0.061)
U-232 + Cs137	59.68%	102.9	255.1	27266	114	0.4469	(0.006,0.159)
U-232 + Cs137	69.25%	83.1	270.3	35945	86	0.3181	(-0.112,0.019)
Co-60	58.72%	112.5	272.5	26084	106	0.3890	(-0.046,0.095)

Two-sided 90% confidence interval.

Due to the higher neutron efficiency of the Detective-X producing measured neutron counts above 30 counts, the standard deviation of the net count rate for the Normal distribution was calculated and a two-side 90% net count rate confidence interval was determined [3].

In all instances, the two-side 90% net count rate confidence intervals contained zero and there is insufficient evidence to conclude that any sample result was above background. As such, the Detective-X results show that gamma radiation does not have an effect on the reported neutron detector count rate.

1.6.3.1. Additional gamma to neutron cross talk test: Shielded Cf-252 and bare Co-60

An additional gamma to neutron cross talk test was performed using the Fulcrum40h (FF105) and Detective-X (21180856) detector systems.

Using a Cf-252 sealed source in a lead shield (to minimize gamma radiation), a measurement was conducted at a neutron count rate well above background to determine the neutron count rate at a low gamma count rate. Without moving the shieled Cf-252 sealed source, a subsequent measurement was conducted by including a bare Co-60 sealed source to generate a high gamma count rate (roughly 15,000 and 20,000 cps). Lastly, a background measurement was collected.

A comparison of the neutron count rate for the shielded Cf-252 and bare Co-60 sealed sources to the neutron count rate for the bare Cf-252 sealed source alone is presented for the Fulcrum40h (FF105) and Detective-X (21180856) detector systems in Table 11 and Table 12, respectively.

Table 11. Additional Fulcrum40h (FF105) gamma to neutron cross talk measurement results.

Nuclides	Dead Time (%)	Live Time (sec)	Real Time (sec)	Gamma (cps)	Neutron (counts)	Neutron (cps)	Two-Sided 90.0% CI (cps)
Background	0.98%	3624.2	3660.0	212	41	0.0113	---
Cf-252 in Pb shield	0.87%	318.2	321.0	614	301	0.9459	---
Cf-252 in Pb shield + Co-60 bare	16.58%	312.0	374.0	19725	322	1.0321	(-0.038,0.210)

Table 12. Additional Detective-X (21180856) gamma to neutron cross talk measurement results.

Nuclides	Dead Time (%)	Live Time (sec)	Real Time (sec)	Gamma (cps)	Neutron (counts)	Neutron (cps)	Two-Sided 90.0% CI (cps)
Background	0.76%	652.6	657.6	219	268	0.4075	---
Cf-252 in Pb shield	1.24%	356.0	360.4	355	2078	5.7655	---
Cf-252 in Pb shield + Co-60 bare	40.72%	215.4	363.4	15188	2061	5.6708	(-0.198,0.387)

As shown in Table 11 and Table 12, the two-sided 90% confidence interval contained zero for both the Fulcrum40h (FF105) and Detective-X (21180856) detector systems. Therefore, there is insufficient evidence to conclude that the neutron count rate for the shielded Cf-252 and bare Co-60 sealed source measurement versus the shielded Cf-252 sealed source alone measurement were different. In conclusion, gamma radiation does not have an effect on the reported neutron detector count rate for either detector system.

2. SUMMARY OF CONCLUSIONS

- The measured average Fulcrum40h efficiency below roughly 300 keV is significantly better (≥20%) than the measured average Detective-X efficiency due to its larger diameter (80-mm versus 65-mm). At energies above roughly 2000 keV, the measured average Detective-X efficiency is slightly better than the measured average Fulcrum40h efficiency due to its larger crystal depth (50-mm versus 30-mm).
- The average Fulcrum40h and the Detective-X resolution as a function of energy are reasonably close with a small advantage to the Fulcrum40h at lower energies and Detective-X at higher energies.
- The Fulcrum40h (FF105) in-situ surface distribution efficiency below 100 keV is significantly better than the Detective-X (21180856). Above 100 keV, the Detective-X (21180856) in-situ surface distribution efficiency exceeds the Fulcrum40h (FF105).
- The Detective-X (21180856) neutron efficiency is roughly 20 to 50 times better (dependent on the Cf-252 moderation configuration) than the Fulcrum40h (FF105). This is expected due to the much larger surface area/volume of the Detective-X neutron detector as compared to the Fulcrum40h detector.
- For the Fulcrum40h (FF105) detector system, pile up rejection/live time correction performance and detector system resolution degrades above ≈11,500 cps (≈10% dead time). For the Detective-X (21180856), pile up rejection/live time correction performance is accurate within 10% at count rates up to ≈36,000 cps (≈70% dead time) and shows no noticeable degradation in resolution as a function of total gamma count rate.
- Fulcrum40h and Detective-X results indicate that gamma radiation does not have an effect on the reported neutron detector count rate.

REFERENCES

[1] G. Gilmore, Practical Gamma-Ray Spectrometry, 2nd Edition, John Wiley, 2008.

[2] Multi-Agency Radiological Laboratory Analytical Protocols Manual, Attachment 20A (NUREG-1576, July 2004).

[3] Strom, Daniel J.; Stansbury, Paul S.. Minimum Detectable Activity When Background Is Counted Longer Than the Sample. Health Physics: September 1992 - Volume 63 - Issue 3 - p 360-361.

APPENDIX A. ORTEC DETECTIVE-X HPGE DETECTOR SYSTEM MANUFACTER DATES

Serial number 20147305 - 05/28/2020

Serial number 20210026 - 06/29/2020

Serial number 21146310 - 05/28/2021

Serial number 21180856 - 06/30/2021

Serial number 22117830 - 04/29/2022

Serial number 22235129 - 08/29/2022

APPENDIX B. MEASUREMENT PLAN

All measurements conducted in Sandia National Laboratories (New Mexico) Building 892, Room 133C.

1 DETECTOR RESPONSE FUNCTION AND EFFICIENCY/RESOLUTION MEASUREMENTS

Order of DRF measurements Fulcrum-40hs (FF106, FF105, FF104, FF108, FF107, FF103), Detective-Xs (21180856, 20210026, 21146310 Stab, 22117830 Stab, 22235129 Stab, 20147305)

Distance (cm)	Height (cm)	Detector Model
100.00	84.00	Fulcrum40h
100.00	83.50	Detective X

1A GAMMA EFFICIENCY AND RESOLUTION

Counter	Purpose	GADRAS Database Source ID	10/7/22 0:00 Activity (uCi)	Approx. Real Time (min)
1	DRF	Background	---	5
2	DRF	241AM_164949	241Am,105.2uCi	5
3	DRF	133BA_2185223	133Ba,85.0uCi	5
4	DRF	137CS_1351202	137Cs,71.5uCi	5
5	DRF	60CO_2186228	60Co,58.6uCi	5
6	DRF	232U_NIST062328	232U,86.9uCi	5

1B NEUTRON EFFICIENCY: FULCRUM40 (FF105) and DET-X (21180856)

Counter	Purpose	GADRAS Database Source ID	GADRAS Database Source ID	10/12/22 0:00 Activity (uCi)	Approx. Real Time (min)
1	DRF	Background	Background	---	5
2	DRF	252CF_1672	Bare	252Cf,10.9uCi	5
3	DRF	252CF_1672	2-cm PE	252Cf,10.9uCi	5
4	DRF	252CF_1672	4-cm PE	252Cf,10.9uCi	5
5	DRF	252CF_1672	8-cm PE	252Cf,10.9uCi	5
6	DRF	252CF_1672	8-cm Borated PE	252Cf,10.9uCi	5
7	DRF	252CF_1672	4-cm PE at 90 degrees	252Cf,10.9uCi	5

2A PILE UP MEASUREMENTS: FULCRUM40 (FF105)

Distance (cm)	Height (cm)
20.00	84.00

Counter	Purpose	GADRAS Database Source ID	11/4/22 0:00 Activity (uCi)	GADRAS Database Source ID	11/4/22 0:00 Activity (uCi)	11/4/22 0:00 Activity (uCi)	Approx. Real Time (min)
1	DRF	Background	---	---	---	---	15
2	DRF	241AM_2179342	241Am,20.2uCi	---	---	241Am,20.2uCi	5
3	DRF	133BA_1278692	133Ba,7.4uCi	---	---	133Ba,7.4uCi	5
4	DRF	137CS_1278693	137Cs,13.7uCi	---	---	137Cs,13.7uCi	5
5	DRF	60CO_2185227	60Co,3.6uCi	---	---	60Co,3.6uCi	5
6	DRF	232U_NIST0623220	232U,8.5uCi	---	---	232U,8.5uCi	5
7	Cs	137CS_2185226	137Cs,122.0uCi	---	---	137Cs,122.0uCi	5
8	Cs	137CS_1351202	137Cs,71.4uCi	---	---	137Cs,71.4uCi	5
9	Cs	137CS_2185225	137Cs,41.4uCi	---	---	137Cs,41.4uCi	5
10	Cs	137CS_1278693	137Cs,13.7uCi	---	---	137Cs,13.7uCi	10
11	Cs	137CS_2185224	137Cs,1.9uCi	---	---	137Cs,1.9uCi	15
12	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_2185226	137Cs,122.0uCi	133Ba,7.4uCi+137Cs,122.0uCi	5
13	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_1351202	137Cs,71.4uCi	133Ba,7.4uCi+137Cs,71.4uCi	5
14	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_2185225	137Cs,41.4uCi	133Ba,7.4uCi+137Cs,41.4uCi	5
15	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_1278693	137Cs,13.7uCi	133Ba,7.4uCi+137Cs,13.7uCi	10
16	CsWithBaHigh	133BA_1278692	133Ba,7.4uCi	137CS_2185224	137Cs,1.9uCi	133Ba,7.4uCi+137Cs,1.9uCi	15
17	CsWithBaHigh	133BA_2185223	133Ba,84.5uCi	137CS_2185226	137Cs,122.0uCi	133Ba,84.5uCi+137Cs,122.0uCi	5
18	CsWithBaHigh	133BA_2185223	133Ba,84.5uCi	137CS_1351202	137Cs,71.4uCi	133Ba,84.5uCi+137Cs,71.4uCi	5
19	CsWithBaHigh	133BA_2185223	133Ba,84.5uCi	137CS_2185225	137Cs,41.4uCi	133Ba,84.5uCi+137Cs,41.4uCi	5
20	CsWithBaHigh	133BA_2185223	133Ba,84.5uCi	137CS_1278693	137Cs,13.7uCi	133Ba,84.5uCi+137Cs,13.7uCi	10
21	CsWithBaHigh	133BA_2185223	133Ba,84.5uCi	137CS_2185224	137Cs,1.9uCi	133Ba,84.5uCi+137Cs,1.9uCi	15
22	Co	60CO_2186229	60Co,115.2uCi	---	---	60Co,115.2uCi	5

2B PILE UP MEASUREMENTS: DET-X (21180856)

Distance (cm)	Height (cm)
25.00	83.50

Counter	Purpose	GADRAS Database Source ID	11/4/22 0:00 Activity (uCi)	GADRAS Database Source ID	11/4/22 0:00 Activity (uCi)	11/4/22 0:00 Activity (uCi)	Approx. Real Time (min)
1	DRF	Background	---	---	---	---	15
2	DRF	241AM_164949	241Am,105.1uCi	---	---	241Am,105.1uCi	5
3	DRF	133BA_2185223	133Ba,84.5uCi	---	---	133Ba,84.5uCi	5
4	DRF	137CS_1351202	137Cs,71.4uCi	---	---	137Cs,71.4uCi	5
5	DRF	60CO_2186228	60Co,58.0uCi	---	---	60Co,58.0uCi	5
6	DRF	232U_NIST062328	232U,86.8uCi	---	---	232U,86.8uCi	5
7	Cs	137CS_2185226	137Cs,122.0uCi	---	---	137Cs,122.0uCi	5
8	Cs	137CS_1351202	137Cs,71.4uCi	---	---	137Cs,71.4uCi	5
9	Cs	137CS_2185225	137Cs,41.4uCi	---	---	137Cs,41.4uCi	5
10	Cs	137CS_1278693	137Cs,13.7uCi	---	---	137Cs,13.7uCi	10
11	Cs	137CS_2185224	137Cs,1.9uCi	---	---	137Cs,1.9uCi	15
12	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_2185226	137Cs,122.0uCi	133Ba,7.4uCi+137Cs,122.0uCi	5
13	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_1351202	137Cs,71.4uCi	133Ba,7.4uCi+137Cs,71.4uCi	5
14	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_2185225	137Cs,41.4uCi	133Ba,7.4uCi+137Cs,41.4uCi	5
15	CsWithBaLow	133BA_1278692	133Ba,7.4uCi	137CS_1278693	137Cs,13.7uCi	133Ba,7.4uCi+137Cs,13.7uCi	10
16	CsWithBaHigh	133BA_1278692	133Ba,7.4uCi	137CS_2185224	137Cs,1.9uCi	133Ba,7.4uCi+137Cs,1.9uCi	15
17	CsWithBaHigh	133BA_1351201	133Ba,42.6uCi	137CS_2185226	137Cs,122.0uCi	133Ba,42.6uCi+137Cs,122.0uCi	5
18	CsWithBaHigh	133BA_1351201	133Ba,42.6uCi	137CS_1351202	137Cs,71.4uCi	133Ba,42.6uCi+137Cs,71.4uCi	5
19	CsWithBaHigh	133BA_1351201	133Ba,42.6uCi	137CS_2185225	137Cs,41.4uCi	133Ba,42.6uCi+137Cs,41.4uCi	5
20	CsWithBaHigh	133BA_1351201	133Ba,42.6uCi	137CS_1278693	137Cs,13.7uCi	133Ba,42.6uCi+137Cs,13.7uCi	10
21	CsWithBaHigh	133BA_1351201	133Ba,42.6uCi	137CS_2185224	137Cs,1.9uCi	133Ba,42.6uCi+137Cs,1.9uCi	15
22	Co	60CO_2186229	60Co,115.2uCi	---	---	60Co,115.2uCi	5

2C TWO SOURCE PILE UP MEASUREMENTS: FULCRUM40 (FF105) and DET-X (21180856)

Using a U-232 sealed source of moderate activity (232U_NIST0623220), a measurement was conducted with minimal dead time to establish reference 583.2 and 2614.5 keV full energy peak count rates.
Without moving the U-232 sealed source, subsequent measurements were conducted by adding a Cs-137 sealed source at various distances to generate count rates ranging between roughly 200 cps and 37,000 cps on both detector systems.

2D ADDITIONAL GAMMA TO NEUTRON CROSS TALK TEST: FULCRUM40 (FF105) AND DET-X (21180856)

Using a Cf-252 sealed source in a lead shield (to minimize gamma radiation), a measurement was conducted at a neutron count rate well above background to determine the neutron count rate at a low gamma count rate.
Without moving the shieled Cf-252 sealed source, a subsequent measurement was conducted by including a bare Co-60 sealed source to generate a high gamma count rate (roughly 15,000 and 20,000 cps). Lastly, a background measurement was collected.

3 IN SITU CALIBRATION MEASUREMENTS: FULCRUM40 (FF105) and DET-X (21180856)

Distance (cm)	Height (cm)
100.00	88.00

Counter	Purpose	GADRAS Database Source ID	10/14/22 0:00 Activity (uCi)	Approx. Real Time (min)
1	Background	Background	---	5
2	00-degrees	241AM_164949	241Am,105.2uCi	5
7	15-degrees	241AM_164949	241Am,105.1uCi	5
12	30-degrees	241AM_164949	241Am,105.1uCi	5
17	45-degrees	241AM_164949	241Am,105.1uCi	5
22	60-degrees	241AM_164949	241Am,105.1uCi	5
27	75-degrees	241AM_164949	241Am,105.1uCi	5
32	90-degrees	241AM_164949	241Am,105.1uCi	5
3	00-degrees	133BA_2185223	133Ba,84.2uCi	5
8	15-degrees	133BA_2185223	133Ba,84.2uCi	5
13	30-degrees	133BA_2185223	133Ba,84.2uCi	5
18	45-degrees	133BA_2185223	133Ba,84.2uCi	5
23	60-degrees	133BA_2185223	133Ba,84.2uCi	5
28	75-degrees	133BA_2185223	133Ba,84.2uCi	5
33	90-degrees	133BA_2185223	133Ba,84.2uCi	5
4	00-degrees	137CS_2185226	137Cs,121.8uCi	5
9	15-degrees	137CS_2185226	137Cs,121.8uCi	5
14	30-degrees	137CS_2185226	137Cs,121.8uCi	5
19	45-degrees	137CS_2185226	137Cs,121.8uCi	5
24	60-degrees	137CS_2185226	137Cs,121.8uCi	5
29	75-degrees	137CS_2185226	137Cs,121.8uCi	5
34	90-degrees	137CS_2185226	137Cs,121.8uCi	5
5	00-degrees	60CO_2186228	60Co,57.6uCi	5
10	15-degrees	60CO_2186228	60Co,57.6uCi	5
15	30-degrees	60CO_2186228	60Co,57.6uCi	5
20	45-degrees	60CO_2186228	60Co,57.6uCi	5
25	60-degrees	60CO_2186228	60Co,57.6uCi	5
30	75-degrees	60CO_2186228	60Co,57.6uCi	5
35	90-degrees	60CO_2186228	60Co,57.6uCi	5
6	00-degrees	232U_NIST062328	232U,86.8uCi	5
11	15-degrees	232U_NIST062328	232U,86.8uCi	5
16	30-degrees	232U_NIST062328	232U,86.8uCi	5
21	45-degrees	232U_NIST062328	232U,86.8uCi	5
26	60-degrees	232U_NIST062328	232U,86.8uCi	5
31	75-degrees	232U_NIST062328	232U,86.8uCi	5
36	90-degrees	232U_NIST062328	232U,86.8uCi	5

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