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Characterization and Analysis of NaI(Tl) and BGO Detectors

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Introduction

There have been many studies concerning the performance characteristics of NaI(Tl) and BGO scintillating crystals, most of which generate data by algorithms rather than from experimentation. Those studies which do deal with collected data, however, usually test only a few detecting units. It was, therefore, the purpose of this project to develop a characterization method (see Appendix 1) and to characterize a large number of scintillators of various sizes and histories as well as to create a performance profile based on the data collected. The energy ranges at which the detectors show relatively good resolution % and photo peak efficiency was also desired for future reference. Enough statistical data were collected and analyzed so that a differentiation between those detectors which perform well and those that do not can be made.

Technical Data

Experimental Setup

One major consideration in any radiation detection experiment is the amount of background radiation included in the overall data. Collected background data indicated that approximately 10% of the experimental data was due to the natural decay of elements found in the structure of the building. In several cases this was of large enough influence to overshadow the desired signals. As a result, the testing apparatus was moved to a low background counting facility. Partially subterranean, the room is constructed of one foot thick Pre-World War II battleship steel. Upon further investigation it was determined that the facility cuts unshielded background readings by a factor of 20 over a 500 live minute duration. The unshielded background readings in the facility are a factor of 2 greater than a standard 3x3 NaI(Tl) Production Counter shielded with six inches of lead. All detectors were tested using the same sources; $^{241}\text{Americium}$, $^{137}\text{Cesium}$, and $^{60}\text{Cobalt}$ with respective activities of $10.0 \pm 0.2 \mu\text{Ci}$, $10.28 \pm 0.02 \mu\text{Ci}$, and $3.69 \pm 0.02 \mu\text{Ci}$. In each case, the source was located 25 cm from the face of the detector along the crystal's primary axis. This was true for all except detectors 42 and 43, which had to be tested from the side due to their being mechanically placed in coincidence. The facility also offers another major benefit to the purity of the collected data. No lead shielding was necessary and the size of the room allowed the testing apparatus to be placed at least 4 feet from each wall. This greatly reduces the possibility of collecting Compton scattering photon, annihilation radiation, and lead X-rays from nearby shielding. ⁽¹⁾⁽⁴⁾

Electronic Setup

The following supplies were utilized for these experiments: RG 71 B/U Coaxial cable, a Bertan model 323 High Voltage Power Supply, an Ortec model 113 Pre-Amp, an Ortec model 114 Pre-Amp Power Supply, a Tennelec model TC244 Amplifier, a Canberra MCA 8100, and an oscilloscope for gain and focus adjustments on the detector base. The pre-amp capacitance remained fixed at 200pF for all 3x3, 5x5, 6x6, and 8x8 detectors. For the 1x1, 2x2, and BGO units the pre-amp was set to 0pF. For those detectors not possessing an integral base an Ortec model 266 base was used. Those requiring a different size base used homemade units. A diagram of the setup and a list of cable lengths is provided.

Cable Lengths:	c	detector to pre-amp	4.25 inches
	d	amp to MCA (ADC in)	2 feet
		(conduit length taken into account)	
	a	power supply to detector	75 feet
	b	pre-amp to amp	94 feet

Unit History

Several detectors had never been used and, therefore, had no operating history. The others range from a couple to nearly thirty years old. Many have dented canisters, possibly resulting in damaged crystals or internal electronics. These things would of course affect the performance of the detector and have therefore been summarized. (see Appendix 3.1)

- NaI(Tl) vs. BGO Detectors

Several differences between NaI(Tl) and BGO detectors are of relevance in this project. For a more complete comparison of their properties see Radiation Detection and Measurement by Glenn Knoll ⁽⁵⁾, specifically page 231, table 8-3. BGO crystals have a little over twice the density of NaI(Tl), meaning that they have a higher Z number. As a result, BGO crystals capture more incident gamma rays. However, statistically, fewer photons make it to the photo cathode of the PMT and they therefore have worse resolution than a NaI(Tl). The fewer photons also requires that a higher gain be used on a BGO. Also, the decay constant of a BGO is longer than that of NaI(Tl), requiring minor alterations on the amplifier.

Data Analysis

The data that have been collected has been archived by the CST Counting Room for future reference. All data, except background, were of a 10 live-minute duration. From this data the detector characteristics have been determined and profile spreadsheets created (see Appendices 3.2 & 3.3). These profiles include each detector's resolution for each of the three sources. This is of primary concern in that, along with the photo peak efficiency, it allows one to discriminate between source peaks so as to better determine unknown sources and to detect several peaks of comparable energies. The peak to total ratio is extremely relevant in that, when used with Monte Carlo data, the intrinsic efficiency of the detector can be determined. When used in conjunction with the photo peak efficiency as well, it allows the overall absolute efficiency to be calculated. The photo peak efficiency, in itself, is necessary and useful in that contributions from Compton scattered photons have little effect on it.⁽²⁾ Since this is the case, the photo peak efficiency is a more accurate measure of the emission rate of the source. It is preferable to use the photo peak efficiency because it is not greatly influenced by variable conditions.⁽²⁾⁽⁶⁾ The Cs ratio is included merely for the comparison of detector performance. Also, the CPS (counts per second) and peak areas are shown as the raw data from which the above characteristics were derived. Explanation of all formulae used appears in Appendix 2.

It was of interest to compensate for the data lost by low level discrimination (LLD) as well as to remove the effects of X-rays from the data. As a result, the reduced data profile was generated. In the case of LLD compensation the first data collected was extended horizontally to the ordinate axis and the new region was added to the data. This was done in the cases of Cesium and Cobalt. X-ray subtraction was performed on both Cesium and Americium. This was the only form of data reduction used on Americium since the X-ray subtraction is roughly equivalent to the LLD cutoff. In the case of Cobalt, the 1173 and 1332 KeV peaks were added to determine a new peak area, peak to total ratio, CPS, and photo peak efficiency.

Graphs

The following graphs are taken directly from the profiles that appear in Appendices 3.2 & 3.3. A reference number was used in the cases where the profile order was inappropriate; a reference number to detector number correspondence table has been included for convenience.

**GRAPH
REFERENCE NUMBERS**

Graph Reference Number	Detector Number
1	41
2	31
3	32
4	33
5	34
6	36
7	37
8	38
9	39
10	40
11	1
12	2
13	3
14	4
15	5
16	6
17	7
18	8
19	9
20	10
21	11
22	12
23	13
24	14
25	15
26	16
27	17
28	18
29	19
30	20
31	21
32	22
33	29
34	24
35	25
36	26
37	27
38	28
39	42
40	43
41	44

NOTE : Due to Non-Responsive behavior, detectors 23, 30, and 35 have intentionally been removed from the graphs.

NaI(Tl) Relative Resolutions

Nal(Tl) Peak to Total Ratio

NaI(Tl) Efficiencies

Nal(Tl) Resolution vs. Log Energy

Nal(Tl) Peak to Total Ratio vs. Log Energy

(Post Data Reduction) Peak to Total Ratio

(Post Data Reduction) Efficiencies

(Post Data Reduction) Peak to Total Ratio vs. Log Energy

BGO Relative Resolutions

BGO Peak to Total Ratio

BGO Efficiencies

BGO Resolution vs. Log Energy

BGO Peak to Total Ratio vs. Log Energy

(Post Data Reduction) BGO Efficiencies

(Post Data Reduction) BGO Peak to Total Ratio

(Post Data Reduction) BGO Peak to Total Ratio vs. Log Energy

Discussion

Several trends appear obvious from the graphed data. It is of great interest that the peak to total ratio is remarkably uniform, though the resolution varies greatly between detectors. The photo peak efficiency is also noticeably consistent, which simply means that the manufacturer machines the crystals to consistent dimensions. Another point of interest is the fact that age does not seem to be a factor in the performance of the detector. From the profiles generated it has been determined that a typically good detector has the following properties:

NaI(Tl)

<u>Size (2x2)</u>	<u>Energy (59.5 KeV)</u>	<u>(662 KeV)</u>	<u>(1173 KeV)</u>	<u>(1332 KeV)</u>
Resolution %	17	8	7	6
Peak/Total	0.9	0.45	0.19	0.15
Efficiency * 1000	1.8	0.7	0.4	0.3

Size (3x3)

Resolution %	16	7	6.5	6
Peak/Total	0.9	0.45	0.19	0.15
Efficiency * 1000	4.0	2.1	1.4	1.2

Size (5x5)

Resolution %	15	7	6	6
Peak/Total	0.9	0.45	0.19	0.15
Efficiency * 1000	8.3	7.0	5.5	4.6

BGO

<u>Size (3x3)</u>	<u>Energy (59.5 KeV)</u>	<u>(662 KeV)</u>	<u>(1173 KeV)</u>	<u>(1332 KeV)</u>
Resolution %	45	12.5	11	10
Peak/Total	0.95	0.7	0.35	0.29
Efficiency * 1000	4.4	4.2	3.6	3

It is very important to note that resolution %, peak to total ratio, and photo peak efficiency (*1000) all seem to decline with increasing energies. This is due to the fact that at higher energies the gamma rays are statistically more likely to escape capture within the crystal. Several anomalies appear in the data and for which an explanation cannot be offered at this time. The most notable anomalies are those dealing with resolution %. Several detectors display extremely bad resolutions. These tend to be in the lower end of the energy scale. Many of the detectors show bad resolution % in the 59.5 KeV Americium peak. However, a few appear to have resolutions, specifically in the 1173 KeV Cobalt peak, that are extremely good. These anomalies are much lower than their fellow detectors with a resolution % between 3 and 5. One possible solution for this activity is given by both Heath and Knoll.⁽³⁾⁽⁷⁾ Ionization within the detecting crystal, and other sources discussed by Knoll, results in statistical fluctuations which invariably effects the resolution of the unit. It also interesting to note that the slope of the Resolution % vs. Log Energy graph, included with this report, is consistent with Heath's determination.⁽³⁾ The graph included in this report, however, is lower on the resolution % scale, implying that the detectors tested were of a better resolution %.

Acknowledgments

I would like to acknowledge the contributions of Malcolm Fowler, whose expertise and guidance were integral to this project.

References

1. R.L. Heath, Scintillation Spectrometry Gamma Ray Spectrum Catalogue, 2nd Ed. Vol. 1, pp. 10-18, U.S. Atomic Energy Commission, 1968.
2. *ibid.* p. 22
3. *ibid.* p. 9, specifically figure 6.
4. Glenn F. Knoll, Radiation Detection and Measurement, 2nd Ed. p. 231, John Wiley and Sons, NY 1989.
5. *ibid.* pp. 230-232, 234-236.
6. *ibid.* pp. 117, 119.
7. *ibid.* pp. 115-116.

Appendix 1

NaI(Tl) and BGO Scintillation Detector Characterization

July, 1994
rev 3.0

1.) Setup :

Set MCA to 1024 channels.
Calibrate spectrum with Cesium 137 source.
Start with positive HV of 1 kV.
Use amplifier shaping time of 1.5 microsec.
Adjust amplifier gain to put Cesium peak near the center of the display (channel 450).
Once this is done, amplifier gain should remain fixed for a given detector.

2.) For Each Tube :

Check the amplifier pole zero and adjust.
In the Steel Room, maximize the pulse amplitude with PMT focus using O-scope.
Adjust amplifier gain (slightly) and HV to place cesium peak in channel 450.

3.) Counting :

Place source at 25 cm from detector face --- 3 runs per tube.
Record jug -- mass -- start time.
Record long enough to a well defined peak --- around 10 minutes.
Begin data acquisition sequence.
At end of run output spectra to VAX.
Collect hardcopies and file.

4.) Report :

For each report - detector size, type, mfg, serial number, VAX data output, and notable comments.
Report HV, resolution, net peak counting rate = (net peak area/count time), photopeak efficiency,
Cs ratio, peak to total ration, etc.
Fill in Excel spreadsheet.

5.) Data :

<u>Nuclide</u>	<u>Energy</u>	<u>Channel</u>
Am (241)	59.5 keV	40.1
Cs (137)	32.0 keV	21.8
	662.0 keV	450.0
Co (60)	1173.0 keV	797.0
	1332.0 keV	905.0

Appendix 2

NaI(Tl) and BGO Profile Formulae

$$\text{Res \%} = \text{Resolution \%} = [\text{Full Width Half Max} / \text{Centroid of Peak}] * 100$$

$$\text{CPS} = \text{Counts Per Second (in peak)} = \text{Peak area} / 600$$

$$\text{Cs Ratio} = \text{Americium or Cobalt Resolution \%} / \text{Cesium Resolution \%}$$

$$\text{Pk/Tot} = \text{Peak Area} / \text{Total Area}$$

$$\text{Eff} = \text{Photopeak Efficiency} = \text{CPS} / \text{DPS}, \text{ where DPS is the Decays per Second of each source:}$$

Americium	DPS = 9.202×10^6
Cesium	DPS = 1.090×10^7
Cobalt	DPS = 6.520×10^6

Reduced Data Profile Formulae (only altered formulae shown)

Americium	$\text{Pk/Tot} = \text{Peak Area} / \text{New Total Area}$	(using only LLD compensation)
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Cesium	$\text{Pk/Tot} = \text{Peak Area} / \text{New Total Area}$	(using LLD compensation and X-ray subtraction)
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Cobalt	$\text{Pk Area} = (1173 \text{ KeV peak area} + 1332 \text{ KeV peak area})$ $\text{Pk/Tot} = \text{New Peak Area} / \text{New Total Area}$ $\text{CPS} = \text{New Peak Area} / 600$ $\text{Eff} = \text{New CPS} / \text{DPS}$	(using LLD compensation and Peak Summation)
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The method used for X-ray subtraction is as follows:

$$\text{New Total} = \text{Old Total} - \text{X-ray net}$$

$$\text{X-ray net} = (\sum X_i - \sum X_j) - [(X_a + X_b) / 2 * (b-a)]$$

where : b = channel endpoint of right side of X-ray peak
a = channel endpoint of left side of X-ray peak
 X_i = Total counts
 X_n = Counts at channel n, where n is an integer

NaI(Tl) TUBE NO.	MFG.	TYPE	SIZE	SERIAL	WELL SIZE (")	VAX OUTPUT SERIAL NUMBER			COMMENTS			
						Am 241	Cs 137	Co 60				
1	Bicron	3mw3/3L	3x3 well	EF-260	1.5 x 1/2	187-028	187-042	187-049	Removed from counter 11			
2	Bicron	3mw/3L	3x3 well		1.5 x 1/2	187-067	187-066	187-068	No focus, damaged well--Counter 5			
3	Harshaw	12sw12-x	3x3 well	JL-636	1.5 x 1/2	187-071	187-069	187-073	EG&G base (266), s/n (1775)			
4	Bicron	3mw3p/3cl	3x3 well	X-851	1.5 x 1/2	192-035	192-031	192-038	Needs High Gain -- Very poor Res across Spectrum			
5	Harshaw	12sw12-x	3x3 well	CJ-910	1.5 x 3/4	192-053	192-051	192-056	EG&G base--Rudolph on Protective can			
6	Harshaw	12sw12-x	3x3 well	EQ-67	1.5 x 3/8	192-058	192-057	192-059	EG&G base			
7	Harshaw	12sw12-x	3x3 well	DV-472	1.5 x 3/8	193-031	193-025	193-036	EG&G base--Removed from 105 (NOV 83)			
8	Harshaw	12sw12-x	3x3 well	CH-63	1.5 x 3/8	193-041	193-040	193-042	EG&G base--Old 101--Am spill, removed (12-12-78)			
9	Bicron	3mw3/3L	3x3 well	I-514	1.5 x 3/8	193-048	193-044	193-051	Well dia. of 3/4"-- marked as #98 (4-4-74)			
10	Bicron	3mq3/3L	3x3 well	EO-053	1.5 x 1/2	193-055	193-053	193-057				
11	Bicron	3mw3/3L-x	3x3 well	HZ-830	1.5 x 1/2	193-074	193-071	193-076	No Gain adjust -- Property #912485			
12	Bicron	3m3p3L	3x3 solid	F-904		194-057	194-056	194-059	OK as of (2-15-74), checked by Carl Orth			
13			3x3 solid			194-062	194-061	194-063	EG&G base-- marked as OLD COUNTER 40			
14	Harshaw	12s12/3	3x3 solid	GF-498		194-083	194-080	194-084	EG&G base-Marked "CNC-11", "CJO Room 209"			
15			3x3 solid			194-073	194-068	194-077	Home-made Base--marked as "72% at 1000V"			
16			3x3 solid			194-088	194-085	194-089	Home-made Base-- Dents in Crystal Cylinder			
17	Harshaw	12s12	3x3 solid	EP-617		194-094	194-091	194-095	EG&G base--Old Counter 50--Bubble in can bottom			
18	Harshaw	12s12	3x3 solid	CC-331		194-097	194-096	194-098	EG&G base			
19	Harshaw	12s12	3x3 solid	ER-194		194-100	194-099	194-101	EG&G base			
20	Harshaw	12s12	3x3 solid	ER-195		194-103	194-102	194-104	EG&G base			
21			3x3 solid			194-106	194-105	194-107	EG&G base--Badly dented cylinder			
22	Harshaw	12s12	3x3 solid	CG-294		194-109	194-108	194-110	EG&G base			
23	Harshaw	12s12	3x3 solid	CZ-516					NON-RESPONSIVE--Given to Tim Benjamin			
24	Bicron	5mw5/5l-x	5x5 well	HZ-536	2.5 x 1/2	196-049	196-048	196-050	No Gain -- Property #912375			
25	Bicron	5mw5/5l-x	5x5 well	HZ-537	2.5 x 1/2	196-052	196-051	196-053	No Gain -- Property #912373			
26	Bicron	5mw5/5l-x	5x5 well	HZ-538	2.5 x 1/2	196-055	196-054	196-058	No Gain -- Property #912376			
27	Bicron	5mw5/5l-x	5x5 well	HZ-539	2.5 x 1/2	196-060	196-059	196-061	No Gain -- Property #912374			
28	Harshaw	24mbw24/5-x	6x6 well	EP-555	5 x 1/4	196-064	196-063	196-066	EG&G base			
29	Bicron	3mw3p/3cl	3x3 well	X-850	1.5 x 1/2	199-059	199-057	199-060	Dented Can -- Removed from CNTR 10 (7-18-94)			
30	Harshaw	8s18-x	2x2 well	EQ-352	1.5 x 1/2				EG&G base --NON RESPONSIVE-- Counter 59			
31	Harshaw	8s18-x	2x2 well	DQ-457	1 x 3/8	201-087	201-086	201-088	EG&G base -- Dented cannister			
32	Harshaw	8s8/2	2x2 solid	GF-499		201-091	201-090	201-092	EG&G base -- CNC-11 CJO Room 209			
33	Harshaw	8s8	2x2 solid	AX-236		201-098	201-098	201-102	EG&G base			
34	Harshaw	6shb2	2x2 solid	BW-745		201-044	202-033	202-045	EG&G base -- Beryllium Window			
35	Harshaw		2x2 solid						EG&G base --NON RESPONSIVE-- Old #33			
36	Harshaw		2x2 solid			202-056	202-050	202-060	EG&G base -- Marked with : "NaI 4 ?"			
37	Harshaw	8s8	2x2 solid	BI-878		202-070	202-068	202-071	EG&G base			
38	Harshaw	8s8/2b	2x2 solid	IE-169		202-078	202-077	202-082				
39	Harshaw		2x2 solid			202-090	202-085	202-091	EG&G base -- Removed from Coinc. Counter			
40	Harshaw		2x2 solid			202-095	202-094	202-096	EG&G base -- Removed from Coinc. Counter			
41	Harshaw	4s4	1x1 solid	BX-379		203-071	203-060	203-073	Homemade base			
42	Bicron	6hw6/5cl	6x6 well	K-859	-----	203-083	203-081	203-084	Coincidence counter -- adjustable height			
43	Bicron	6hw6/5cl	6x6 well	K-338	-----	203-089	203-088	203-090	Coincidence counter -- fixed position			
44	Bicron		8x8 well		3 x 3/8	206-028	206-026	206-032				
45									KEG			
BGO									Higher gain and greater shaping time (6)			
1	Harshaw	6s6-b	1.5x1.5	LQ-572		207-060	207-056	207-059	Homemade base			
2	Harshaw	12mb12/3a-BGO	3x3 solid	DD-937		207-063	207-062	207-065	LANL Prop assigned Va.State Univ. c/o Stronach			
3	Harshaw	12mb12/3a-BGO	3x3 solid	DE-200		207-068	207-067	207-071				
4	Harshaw	12mb12/3a-BGO	3x3 solid	DE-201		207-073	207-072	207-074	HV & Signal jacks improperly marked			
5	Harshaw	12mb12/3a-BGO	3x3 solid	DE-202		207-077	207-076	207-083				

Mat(T)	MPQ	TYPE	SIZE	SERIAL	HV (kV)	Am 241 (10.0 microCi)						Co 137 (10.26 microCi)						Co 60 (3.69 microCi)															
						RES %	Co RATIO	PE AREA	PE/TOTAL	CPS	EFF	RES %	PE AREA	PE/TOTAL	CPS	EFF	RES %	Co RATIO	PE AREA	PE/TOTAL	CPS	EFF											
UNIT	NO.					59.5 keV peak						662 keV peak								1173 keV peak							1332 keV peak						
1	Bicron	3mw3/3L	3x3 well	EF-260	1.00	21.43	2.16	318719	0.91	531.20	3.46373	9.93	239513	0.45	393.19	2.15848	9.93	1.00	94085	0.18	156.81	1.45216	0.00	74094	0.14	123.48	1.13642						
2	Bicron	3mw3/3L	3x3 well		1.05	18.48	2.18	334112	0.89	556.85	3.63102	8.46	240183	0.45	400.31	2.19755	7.43	0.88	99353	0.19	165.59	1.53347	6.85	0.81	70585	0.14	117.64	1.08260					
3	Harshaw	12w12-u	3x3 well	J-436	1.06	14.44	1.97	382214	0.91	637.02	4.18378	7.33	240773	0.44	401.29	2.20294	8.47	0.88	94321	0.18	157.20	1.45580	6.12	0.83	75419	0.14	125.70	1.18674					
4	Bicron	3mw3p3d	3x3 well	X-651	1.06	47.14	2.52	33282	0.89	56.47	0.36170	18.68	216343	0.48	360.67	1.97942		0.00	154737	0.32	287.90	2.38829	0.00	0.00	0.00	0.00	0.00000						
5	Harshaw	12w12-u	3x3 well	CJ-910	1.00	17.02	2.03	380944	0.85	634.91	4.13998	8.39	233938	0.43	369.90	2.14041	6.89	0.82	91677	0.18	152.80	1.41499	6.18	0.74	74120	0.14	123.53	1.13682					
6	Harshaw	12w12-u	3x3 well	EO-67	1.02	26.53	2.39	374772	0.85	624.82	4.07290	10.67	241544	0.44	402.57	2.21000	11.05	1.04	110061	0.21	183.44	1.69874	0.00	70360	0.13	117.27	1.07915						
7	Harshaw	12w12-u	3x3 well	CH-910	1.01	28.89	2.88	375300	0.88	625.90	4.07864	10.04	238422	0.44	394.70	2.16879	8.19	0.82	92284	0.18	163.78	1.42390	7.74	0.77	74122	0.15	123.54	1.13685					
8	Harshaw	12w12-u	3x3 well	DV-472	1.00	18.89	2.13	377149	0.86	626.58	4.09673	8.85	239310	0.44	398.88	2.18956	7.59	0.86	88167	0.17	146.95	1.36082	7.80	0.86	80403	0.16	134.01	1.23218					
9	Harshaw	12w12-u	3x3 well	CA-43	1.00	18.89	2.13	377149	0.86	626.58	4.09673	8.85	239310	0.44	398.88	2.18956	7.59	0.86	88167	0.17	146.95	1.36082	7.80	0.86	80403	0.16	134.01	1.23218					
10	Bicron	3mw3/3L	3x3 well	I-614	1.09	11.96	1.79	358817	0.86	596.00	3.89951	6.67	239381	0.45	398.97	2.19021	3.27	0.49	94917	0.19	158.20	1.46500	5.45	0.82	78423	0.15	127.37	1.17214					
11	Bicron	3mw3/3L	3x3 well	EO-053	1.01	13.04	1.97	353813	0.86	585.86	3.84621	6.64	235061	0.44	391.77	2.15068	5.02	0.78	81888	0.18	153.11	1.41791	4.79	0.72	77259	0.15	126.83	1.18567					
12	Bicron	3mw3/3L-u	3x3 well	H2-830	1.00	12.90	1.79	354013	0.89	590.02	3.84730	7.00	236785	0.45	394.64	2.16846	5.56	0.79	95201	0.19	156.67	1.46938	5.11	0.73	73388	0.14	122.31	1.12589					
13	Bicron	3mw3p3L	3x3 solid	F-804	1.11	13.33	2.15	359085	0.91	598.48	3.90242	8.21	238515	0.45	397.53	2.18228	5.06	0.81	91630	0.18	152.72	1.41427	4.92	0.79	77977	0.15	125.96	1.19587					
14			3x3 solid		1.09	18.48	2.31	370333	0.90	617.22	4.02466	8.00	242194	0.45	403.66	2.21595	5.53	0.82	97321	0.19	162.20	1.50210	8.24	0.78	75277	0.15	125.47	1.15459					
15	Harshaw	12x12/3	3x3 solid	GF-498	1.08	12.22	1.84	373721	0.91	622.67	4.06146	6.85	243135	0.45	405.23	2.22456	5.91	0.89	94101	0.18	156.84	1.45240	4.99	0.75	78957	0.15	131.60	1.21100					
16			3x3 solid		1.09	18.89	2.49	387977	0.91	646.63	4.21641	7.90	281288	0.45	418.78	2.29897	6.11	0.90	96772	0.19	164.82	1.52480	5.77	0.76	80758	0.15	134.60	1.23863					
17			3x3 solid		1.02	14.44	1.98	389689	0.92	649.78	4.23687	7.30	253362	0.46	422.27	2.31813	5.79	0.79	100181	0.19	166.97	1.54825	5.57	0.76	82358	0.15	137.26	1.26317					
18	Harshaw	12x12	3x3 solid	EP-817	1.02	16.67	2.21	378491	0.91	627.48	4.09168	7.53	247302	0.46	412.17	2.26268	6.88	0.78	94280	0.18	157.08	1.45470	5.38	0.71	79415	0.15	131.91	1.21389					
19	Harshaw	12x12	3x3 solid	CC-331	1.04	17.78	2.33	387925	0.91	646.54	4.21584	7.64	250335	0.46	417.23	2.29043	6.18	0.81	99741	0.19	166.24	1.53946	6.08	0.80	80963	0.15	134.94	1.24177					
20	Harshaw	12x12	3x3 solid	ER-194	1.02	14.13	2.06	384644	0.90	610.81	3.96283	6.87	241842	0.45	403.07	2.21273	5.38	0.78	94789	0.18	157.95	1.46271	5.10	0.74	77982	0.15	129.97	1.19605					
21			3x3 solid		1.01	17.39	2.16	385439	0.90	609.07	3.97147	7.96	239022	0.46	398.37	2.18692	6.51	0.82	97982	0.19	163.25	1.51184	5.97	0.75	80386	0.15	133.98	1.23292					
22			3x3 solid		1.06	28.41	2.57	378027	0.90	630.06	4.10627	11.06	237231	0.44	395.39	2.17064	10.47	0.95	62639	0.13	104.73	0.96989	0.00	78888	0.16	131.45	1.20984						
23	Harshaw	12x12	3x3 solid	CG-294	1.10	14.44	1.92	371246	0.92	618.74	4.03458	7.54	240267	0.46	400.48	2.19831	6.51	0.88	93889	0.18	156.48	1.44913	5.96	0.79	75895	0.15	126.49	1.16404					
24	Harshaw	12x12	3x3 solid	CZ-516					0.00	0.00000	0.00000			0.00	0.00000	0.00000				0.00	0.00000	0.00000			0.00	0.00000	0.00000						
25	Bicron	3mw3p3d	3x3 well	X-650	1.09	15.22	2.21	97781	0.86	162.94	1.06243	6.89	217788	0.46	382.88	1.99264	5.94	0.86	88884	0.18	143.11	1.32527	5.37	0.78	72861	0.15	121.10	1.11444					
26	Bicron	5mw5/6-u	5x5 well	H2-536	1.00	13.83	1.82	764774	0.90	1274.82	8.31132	7.59	777729	0.51	1296.22	7.11580	6.76	0.89	339928	0.22	586.55	5.24684	6.39	0.84	303889	0.20	506.45	4.66060					
27	Bicron	5mw5/6-u	5x5 well	H2-537	1.06	14.96	2.14	767909	0.89	1279.88	8.34839	6.81	740071	0.49	1233.45	6.77125	5.98	0.82	306062	0.23	601.00	5.56572	5.22	0.77	298103	0.19	496.84	4.57216					
28	Bicron	5mw5/6-u	5x5 well	H2-538	1.01	15.22	2.04	749438	0.90	1249.06	8.14485	7.44	765858	0.51	1259.76	6.91670	6.80	0.89	353788	0.23	589.61	5.46024	5.70	0.77	303455	0.20	506.76	4.65425					
29	Bicron	5mw5/6-u	5x5 well	H2-539	1.02	15.22	2.01	762817	0.90	1271.36	8.29005	7.56	775817	0.52	1293.03	7.09631	6.19	0.82	381689	0.23	602.82	5.58250	5.78	0.78	301114	0.20	501.86	4.61634					
30	Harshaw	8x8-u	2x2 well	EO-652					0.00	0.00000	0.00000			0.00	0.00000	0.00000				0.00	0.00000	0.00000			0.00	0.00000	0.00000						
31	Harshaw	8x8-u	2x2 well	DQ-457	1.06	43.18	3.01	180690	0.90	260.98	1.63656	14.35	74634	0.35	124.39	0.68288		0.00		0.00	0.00000	0.00000			0.00	0.00000	0.00000						
32	Harshaw	8x8/2	2x2 solid	GF-499	1.04	14.13	2.18	171501	0.92	288.84	1.86382	6.47	79620	0.36	133.03	0.73031	6.43	0.84	28039	0.14	46.73	0.43277	4.81	0.74	22124	0.11	36.87	0.33953					
33	Harshaw	8x8	2x2 solid	AX-236	1.01	19.87	2.47	81276	0.44	138.48	0.88328	7.91	81278	0.37	136.48	0.74363	6.27	0.79	28948	0.14	48.24	0.44879	5.66	0.70	22065	0.11	36.78	0.33842					
34	Harshaw	8x8/2	2x2 solid	BW-745	1.04	45.56	3.04	69692	0.77	118.49	0.78956	15.00	8345	0.14	13.91	0.07635		0.00		0.00	0.00000	0.00000			0.00	0.00000	0.00000						
35	Harshaw	8x8	2x2 solid						0.00	0.00000	0.00000			0.00	0.00000	0.00000				0.00	0.00000	0.00000			0.00	0.00000	0.00000						
36	Harshaw	8x8	2x2 solid		1.00	20.00	2.26	178816	0.91	298																							

BGO UNIT NO.	MPG.	TYPE	SIZE	SERIAL	HV (kV)	Am 241 (10.0 microCi)					Cs 137 (10.28 microCi)					Co 60 (3.69 microCi)					1332 keV peak							
						59.5 keV peak					662 keV peak					1173 keV peak					1332 keV peak							
						RES %	Cs RATIO	PE AREA	PE/TOTAL	CPS	EFF	RES %	PE AREA	PE/TOTAL	CPS	EFF	RES %	Cs RATIO	PE AREA	PE/TOTAL	CPS	EFF	RES %	Cs RATIO	PE AREA	PE/TOTAL	CPS	EFF
1	Harshaw	6x6-b	1.5x1.5	LO-572	1.00	51.39	3.13	114922	0.97	191.54	1.24893	16.41	102625	0.65	171.04	0.93896		0.00	45192	0.29	75.32	0.69752		0.00	31548	0.20	52.58	0.45367
2	Harshaw	12mb12/3a-BGO	3x3 solid	DO-937	1.00	40.79	3.24	403884	0.95	873.14	4.38928	12.58	482800	0.71	771.33	4.23437		0.00	237651	0.35	396.09	3.66803		0.00	195057	0.29	325.10	2.59165
3	Harshaw	12mb12/3a-BGO	3x3 solid	DE-200	1.00	45.83	3.59	401831	0.95	869.72	4.36897	12.78	464205	0.70	763.68	4.19233	11.60	0.91	236335	0.35	393.89	3.64772		0.00	196065	0.29	326.78	3.00715
4	Harshaw	12mb12/3a-BGO	3x3 solid	DE-201	1.00	46.25	3.61	402196	0.92	870.33	4.37094	12.80	422131	0.68	703.55	3.66227	11.52	0.90	230182	0.34	383.64	3.55275	10.10	0.79	196406	0.29	327.34	3.01238
5	Harshaw	12mb12/3a-BGO	3x3 solid	DE-202	1.00	43.06	3.54	412710	0.94	687.85	4.48520	12.17	494707	0.70	757.85	4.16033	9.74	0.80	233351	0.35	388.92	3.60166	9.21	0.76	199179	0.30	331.97	3.06491

Appendix 3.3

Inst ID	UNIT	MFG.	TYPE	SIZE	SERIAL	HV (kV)	Am 241 (10.0 microCi)				Ca 137 (10.28 microCi)				Ca 40 (3.89 microCi)				SUMMATION OF PEAKS				
							EFF	PK AREA	NETOTAL	CPM	EFF	PK AREA	NETOTAL	CPM	EFF	PK AREA	NETOTAL	CPM	PK AREA	NETOTAL	CPM	EFF	
1	Bicron	3mm/3/3L	3x3 well	EF-260	1.00	21.43	2.16	318719	0.97	531.20	3.484	9.93	239513	0.45	393.19	2.158	9.93	1.00	1.00	168179	0.31	280.30	2.579
2	Bicron	3mm/3/3L	3x3 well	EF-260	1.05	18.48	2.18	334112	0.97	556.85	3.631	8.46	240183	0.46	400.31	2.186	8.46	0.81	0.81	169938	0.32	283.23	2.608
3	Harshaw	12mm/12-x	3x3 well	JL-036	1.06	14.44	1.97	382214	0.97	637.02	4.154	7.35	240773	0.45	401.29	2.203	7.35	0.83	0.83	169740	0.31	282.90	2.603
4	Bicron	3mm/3/3/3d	3x3 well	X-651	1.06	47.14	2.52	323282	0.97	55.47	0.362	18.66	216343	0.45	389.57	1.973	8.09	0.00	0.00	189580	0.34	282.63	2.601
5	Harshaw	12mm/12-x	3x3 well	CJ-910	1.00	17.02	2.03	380944	0.97	634.91	4.140	8.39	233938	0.45	389.90	2.140	8.09	0.74	0.74	185797	0.32	276.33	2.543
6	Harshaw	12mm/12-x	3x3 well	EQ-67	1.02	25.53	2.39	374772	0.97	624.82	4.073	10.67	241544	0.45	402.57	2.210	11.05	1.04	1.04	189421	0.34	300.70	2.582
7	Harshaw	12mm/12-x	3x3 well	DW-472	1.01	28.69	2.88	375300	0.97	625.50	4.079	10.74	236822	0.46	394.70	2.197	8.19	0.82	0.82	166376	0.32	277.28	2.582
8	Harshaw	12mm/12-x	3x3 well	CH-63	1.00	18.69	2.13	371498	0.97	628.58	4.099	8.95	239310	0.45	398.85	2.190	7.59	0.86	0.86	166970	0.32	280.95	2.585
9	Bicron	3mm/3/3L	3x3 well	CH-63	1.09	11.96	1.79	356817	0.97	588.03	3.900	6.67	239381	0.46	398.97	2.190	6.48	0.82	0.82	171340	0.33	285.57	2.628
10	Bicron	3mm/3/3L	3x3 well	EQ-053	1.01	13.04	1.97	353913	0.97	589.68	3.848	6.84	235061	0.45	391.77	2.161	5.02	0.76	0.76	169185	0.33	281.84	2.595
11	Bicron	3mm/3/3L-x	3x3 well	FZ-804	1.00	12.50	1.79	354013	0.97	590.02	3.847	6.00	238785	0.45	394.64	2.165	5.11	0.73	0.73	168569	0.32	280.98	2.586
12	Bicron	3mm/3/3L	3x3 solid	F-904	1.11	13.33	2.15	359085	0.97	588.48	3.902	6.21	238516	0.46	397.53	2.182	5.06	0.81	0.81	169607	0.33	282.68	2.601
13			3x3 solid		1.09	18.48	2.24	370333	0.97	617.22	4.025	8.00	242194	0.46	403.66	2.216	6.53	0.82	0.82	172600	0.33	287.67	2.647
14	Harshaw	12x12/3	3x3 solid	GF-498	1.08	12.22	1.84	373721	0.97	622.87	4.061	6.95	243135	0.46	405.23	2.225	5.91	0.86	0.86	179580	0.33	298.22	2.754
15			3x3 solid		1.09	18.69	2.49	387877	0.97	646.63	4.217	7.80	251268	0.46	418.78	2.259	6.11	0.80	0.80	182539	0.34	290.44	2.604
16			3x3 solid		1.02	14.44	1.98	386989	0.97	649.76	4.237	7.30	253362	0.47	422.27	2.318	5.79	0.79	0.79	182539	0.34	290.44	2.604
17	Harshaw	12x12	3x3 solid	EP-617	1.02	16.67	2.21	378491	0.97	627.49	4.082	7.53	247302	0.47	412.17	2.263	5.85	0.78	0.78	173665	0.33	289.44	2.604
18	Harshaw	12x12	3x3 solid	CC-331	1.04	17.78	2.33	387825	0.97	646.94	4.216	7.84	250335	0.46	417.23	2.280	6.18	0.81	0.81	180704	0.33	301.17	2.772
19	Harshaw	12x12	3x3 solid	ER-184	1.02	14.13	2.06	366484	0.97	610.81	3.963	6.87	241642	0.46	403.07	2.213	5.38	0.78	0.78	172751	0.33	287.92	2.650
20	Harshaw	12x12	3x3 solid	EP-195	1.01	17.39	2.16	365439	0.97	609.07	3.971	7.96	239022	0.46	396.37	2.167	6.51	0.75	0.75	178338	0.34	297.23	2.735
21			3x3 solid		1.08	28.41	2.37	378027	0.97	630.05	4.109	11.06	237231	0.45	395.39	2.171	10.47	0.95	0.95	141707	0.28	236.18	2.173
22	Harshaw	12x12	3x3 solid	CC-294	1.10	14.44	1.92	371246	0.97	618.74	4.035	7.54	240287	0.46	400.45	2.186	6.51	0.86	0.86	169784	0.32	282.87	2.604
23			3x3 solid								0.000					0.000			0	0.00	0.00	0.000	
24	Bicron	3mm/3/3/3d	3x3 well	X-650	1.09	15.22	2.21	97781	0.91	162.94	1.062	6.89	217788	0.45	362.96	1.993	5.84	0.86	0.86	158525	0.32	264.21	2.431
25	Bicron	5mm/5/5L-x	5x5 well	HZ-536	1.00	13.83	1.82	764774	0.96	1274.62	8.311	7.59	1296.22	0.51	1296.22	7.116	6.76	0.89	0.89	643798	0.42	1073.00	8.974
26	Bicron	5mm/5/5L-x	5x5 well	HZ-537	1.05	14.58	2.14	787909	0.96	1279.85	8.345	6.81	740071	0.49	1233.45	6.771	5.58	0.77	0.77	656705	0.42	1087.84	10.103
27	Bicron	5mm/5/5L-x	5x5 well	HZ-538	1.01	15.22	2.04	749438	0.95	1249.06	8.145	7.44	755858	0.51	1259.76	6.916	6.80	0.89	0.89	657223	0.42	1095.37	10.060
28	Bicron	5mm/5/5L-x	5x5 well	HZ-539	1.02	15.22	2.01	762817	0.96	1271.35	8.290	7.56	775817	0.51	1293.03	7.098	6.19	0.82	0.82	662803	0.42	1104.87	10.186
29	Harshaw	8x8-x	2x2 well	EO-653	1.00	43.18	2.01	150590	0.97	250.98	1.637	14.35	74834	0.35	124.39	0.683	5.43	0.00	0.00	48378	0.24	82.30	0.757
30	Harshaw	8x8-x	2x2 well	DO-453	1.06	14.13	2.18	171501	0.97	285.84	1.244	6.47	79820	0.37	133.03	0.790	5.43	0.84	0.84	50163	0.24	83.61	0.769
31	Harshaw	8x8/2b	2x2 solid	AX-236	1.01	19.57	2.47	81276	0.94	135.48	0.883	7.31	81276	0.38	135.48	0.744	6.27	0.79	0.79	51010	0.24	85.02	0.782
32	Harshaw	8x8/2	2x2 solid	BW-745	1.04	45.56	3.04	69692	0.84	118.49	0.780	15.00	8345	0.13	13.91	0.078	0.00	0.00	5304	0.10	8.84	0.081	
33	Harshaw	2x2 solid								298.03	1.943	8.87	91553	0.38	132.59	0.838	7.03	0.79	0.79	59486	0.20	80.14	0.712
34	Harshaw	2x2 solid								289.74	1.889	8.33	90126	0.36	133.54	0.733	6.35	0.76	0.76	48188	0.23	85.31	0.728
35	Harshaw	2x2 solid								287.89	1.877	8.35	91081	0.37	135.14	0.742	6.36	0.78	0.78	49845	0.24	82.58	0.740
36	Harshaw	2x2 solid								278.21	1.814	7.35	87627	0.30	79.71	0.478	5.89	0.80	0.80	28170	0.18	43.82	0.401
37	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
38	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
39	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
40	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
41	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
42	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
43	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
44	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
45	Harshaw	2x2 solid								268.81	1.753	10.07	47293	0.30	78.82	0.433	8.75	0.87	0.87	27959	0.20	46.80	0.429
BGO																							
1	Harshaw	8x8-b																					
2	Harshaw	2mm/12/3a-85	3x3 solid	DO-337	1.00	40.79	3.24	403884	0.96	673.14	4.389	12.58	462800	0.72	771.33	4.234		0.00	0.00	432708	0.63	721.18	6.837

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