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Measured Gamma Spectra Behind Various
Thicknesses of Beryllium, Beryllium
Oxide, and Lithium Hydride

P. W. Schreiber

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MEASURED GAMMA SPECTRA BEHIND
VARIOUS THICKNESSES OF BERYLLIUM,
BERYLLIUM OXIDE, AND LITHIUM HYDRIDE

Paul W. Schreiber

June 1961

UNITED STATES AIR FORCE

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ABSTRACT:

Angular gamma spectral data measured behind various thicknesses of beryllium, beryllium oxide, and lithium hydride at the GE-ANPD Source Plate Facility located at Battelle Memorial Institute are reported. Measurements were made with an 8-inch-high by 8-inch-diameter NaI(Tl) scintillation spectrometer. The contract was terminated before the collimated spectrometer was calibrated. However, a tentative method for approximating the response functions from measured data and available Monte Carlo calculations is given.

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The author wishes to acknowledge the excellent work done on this study by E. M. Epstein, R. W. Klingensmith, and W. Lendgren of the Battelle Memorial Institute staff.

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I. INTRODUCTION

Angular gamma spectral measurements completed at the GE-ANPD Source Plate Facility at Battelle Memorial Institute are given in this report. Measurements were made behind various thicknesses of beryllium, beryllium oxide, and lithium hydride with an 8-inch-high by 8-inch-diameter NaI(Tl) collimated scintillation spectrometer. The data reported are pulse height distributions obtained from a 200-channel analyzer. No attempt was made to unfold the spectra from the measured pulse height distributions.

Because of the termination of the ANP contract, pulse height distributions for known monochromatic sources were not obtained for the collimated spectrometer. However, pulse height distributions were measured for point sources located on the crystal axis. The collimator and shield were not used for these measurements. A tentative method, using these data and available Monte Carlo calculations, is given for estimating the response functions of the collimated spectrometer. Because of the inherent errors associated with unfolding the spectra if the response functions are not accurately known, it is suggested that the response functions be used to convert calculated spectra to pulse height distributions when comparisons are made.

II. DESCRIPTION OF THE EXPERIMENT

A diagram of a typical experimental arrangement is shown in Figure 1. The slab array of the test material was placed adjacent to the source plate, and the end of the collimator was placed adjacent to the opposite face of the test material. Measurements were made with the collimator directed along the centerline and at angles of 30° and 45° to the centerline in a horizontal plane. Descriptions of the Source Plate Facility, test materials, and collimated spectrometer are given in the following paragraphs.

The Source Plate Facility consists of a 1-megawatt reactor, a thermal column 12-feet long stacked with high-purity graphite blocks, a source plate, and a shielding tank. The physical arrangement of the reactor core, thermal column, and shielding tank, is shown in Figure 2. In order to increase the thermal flux at the end of the thermal column, 29 per cent of the graphite was removed from the center

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Figure 1. Diagram of experimental arrangement

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Fig. 2 - G. E. Source Plate Facility (977C669)

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of the column. With this graphite removed, the ratio of thermal to epithermal flux was approximately 67. Slab arrays are placed in the shielding tank (15 feet by 15 feet by 12-1/2 feet) adjacent to the source plate. A more complete description of the facility may be found in reference 1.

The active fission plate is made of a highly enriched nickel-plated uranium foil jacketed in aluminum. The specifications of the fission plate are listed below.

Plate Diameter

Over-all	28-3/8 $\pm$ 1/16 inch
Core	28.0 inches

Plate Thickness

Over-all	0.070 inch (nominal)
Core	0.0199 inch (uranium)
	0.0014 inch (nickel)
Cladding	0.025 inch (nominal)

Plate Material

Cladding	25 aluminum
Core	Nickel-plated uranium-235
	93.14 per cent enrichment

The complete source plate assembly consists of an aluminum frame containing the fission plate, electrical-heater plate, resistance thermometers, and Lavite spacers. This assembly is held in place by an aluminum holder. A diagram of all distances and materials required for calculations is shown in Figure 3. The 2-1/2-inch lead plate is a gamma shield. The boral curtain on the pool side of the source plate assembly minimizes power changes in the fission plate due to neutron reflection from shielding specimens.

A radial map of the neutron flux distribution at the fission plate is shown in Figure 4. This map may be used to describe the source in polar coordinates. In previous calculations the source distribution was approximated by the equation

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Fig. 3 - Diagram of Distances and Materials for Calculations (737D931)

Fig. 4 - Radial Map of Neutron Flux Distribution (683E301)

$$P(\gamma) = 3.012 \times 10^{-4} \cos 0.0232\gamma \text{ where}$$

$P(\gamma)$ is the power in watts/cm² at radius γ normalized to one watt.

Three 4-inch-thick slabs and one 9-inch-thick slab were used to form the beryllium oxide slab arrays. All slabs were 35 inches by 35 inches. The slabs were mounted in 6-inch-thick steel frames. Details of the slabs are shown in Figure 5, and a list of the slabs is given in Table I.

The beryllium consisted of seven slabs 4 inches thick and one slab 4-1/2 inches thick. Each slab was composed of three beryllium logs (16 inches by 51 inches) held in place by an aluminum frame. A list of the slabs is given in Table II, and a diagram of a slab array is shown in Figure 6.

The lithium hydride was enclosed in aluminum cans. A diagram of a typical can is shown in Figure 7. One 16-inch slab, two 12-inch slabs, one 6-inch slab, and two 4-inch slabs were available to form the slab arrays. All slabs were approximately 48 inches by 48 inches.

Spectral measurements were made with a collimated thallium-activated sodium iodide crystal. The crystal consists of two 8-inch-diameter by 4-inch-high crystals optically coupled and mounted as one crystal. The crystal is enclosed in an aluminum can with MgO powder around the surfaces as shown in Figure 8. Three Vycor 3-inch-diameter windows are optically coupled to the end of the crystal. Three 3-inch-diameter photomultiplier tubes are optically coupled to the Vycor windows. Signals from the three tubes are combined and fed to a cathode follower and then to a 200-channel analyzer. Additional information may be found in references 2 and 3.

Measurements behind the beryllium oxide slab arrays were made with the 8-inch by 8-inch NaI crystal. After these measurements were completed, the crystal was damaged. In order to repair the crystal, it was necessary to remove 1/2 inch from the face adjacent to the photomultipliers. Measurements behind beryllium and lithium hydride slab arrays were made with the repaired crystal.

AL. FRAMES FOR B= SLAB ELEVATION SIDE VIEW SECTION A-A
THRU B= SLABDETAIL SHOWING
B= SLAB SEQUENCE

1) ALL DIMENSIONS NOMINAL.
NOTES

Fig. 5 - Details of Slabs (682E874)

STEEL FRAMES FOR BeO SLABS

Fig. 6 - Detail Showing BeO Slab Sequence

REV	DATE	DESCRIPTION	BY	CHKD
1		ASSEMBLY	X	
2		ASSEMBLY	X	
3		SIDE PLATES	C	
4		SIDE PLATES	C	
5		COVER PLATE	C	
6		ETC	C	

Notes:

1. 405 FULL PENETRATING WELDS
2. 0.50 PSI TEST PRESSURE FOR WELDED JOINTS
3. LEAKS ONE END PLATE FROM 5 GALLON CAN
4. LEAKS TWO END PLATES FROM 5 GALLON CAN
5. LEAKS THREE END PLATES FROM 5 GALLON CAN
6. LEAKS FOUR END PLATES FROM 5 GALLON CAN
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70. LEAKS SIXTY EIGHT END PLATES FROM 5 GALLON CAN
71. LEAKS SIXTY NINE END PLATES FROM 5 GALLON CAN
72. LEAKS SEVENTY END PLATES FROM 5 GALLON CAN
73. LEAKS SEVENTY ONE END PLATES FROM 5 GALLON CAN
74. LEAKS SEVENTY TWO END PLATES FROM 5 GALLON CAN
75. LEAKS SEVENTY THREE END PLATES FROM 5 GALLON CAN
76. LEAKS SEVENTY FOUR END PLATES FROM 5 GALLON CAN
77. LEAKS SEVENTY FIVE END PLATES FROM 5 GALLON CAN
78. LEAKS SEVENTY SIX END PLATES FROM 5 GALLON CAN
79. LEAKS SEVENTY SEVEN END PLATES FROM 5 GALLON CAN
80. LEAKS SEVENTY EIGHT END PLATES FROM 5 GALLON CAN
81. LEAKS SEVENTY NINE END PLATES FROM 5 GALLON CAN
82. LEAKS EIGHTY END PLATES FROM 5 GALLON CAN
83. LEAKS EIGHTY ONE END PLATES FROM 5 GALLON CAN
84. LEAKS EIGHTY TWO END PLATES FROM 5 GALLON CAN
85. LEAKS EIGHTY THREE END PLATES FROM 5 GALLON CAN
86. LEAKS EIGHTY FOUR END PLATES FROM 5 GALLON CAN
87. LEAKS EIGHTY FIVE END PLATES FROM 5 GALLON CAN
88. LEAKS EIGHTY SIX END PLATES FROM 5 GALLON CAN
89. LEAKS EIGHTY SEVEN END PLATES FROM 5 GALLON CAN
90. LEAKS EIGHTY EIGHT END PLATES FROM 5 GALLON CAN
91. LEAKS EIGHTY NINE END PLATES FROM 5 GALLON CAN
92. LEAKS NINETY END PLATES FROM 5 GALLON CAN
93. LEAKS NINETY ONE END PLATES FROM 5 GALLON CAN
94. LEAKS NINETY TWO END PLATES FROM 5 GALLON CAN
95. LEAKS NINETY THREE END PLATES FROM 5 GALLON CAN
96. LEAKS NINETY FOUR END PLATES FROM 5 GALLON CAN
97. LEAKS NINETY FIVE END PLATES FROM 5 GALLON CAN
98. LEAKS NINETY SIX END PLATES FROM 5 GALLON CAN
99. LEAKS NINETY SEVEN END PLATES FROM 5 GALLON CAN
100. LEAKS NINETY EIGHT END PLATES FROM 5 GALLON CAN
101. LEAKS NINETY NINE END PLATES FROM 5 GALLON CAN
102. LEAKS ONE HUNDRED END PLATES FROM 5 GALLON CAN

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS DECIMALS ANGLES		DRAWN DATE BY CHECKED DATE BY		SALT CAN		GENERAL NOTES	
ALL SURFACES MATERIAL GWT. 0.000		MFG DATE		SCALE		SIZE	
G. 0.000		MFG		SCALE		SIZE	
G. 0.000		MFG		SCALE		SIZE	

TABLE I
LIST OF BERYLLIUM SLABS

Slab No.	Log No.	Specific Gravity	Average Thickness (inches)
1	1	1.804	4.007
	2	1.848	4.018
	3	1.855	4.015
2	2	1.850	4.012
	5	1.860	4.008
	6	1.840	4.011
3	7	1.840	4.004
	8	1.840	4.018
	9	1.830	4.010
4	10	1.843	4.004
	14	1.840	4.018
	15	1.840	4.010
5	16	1.850	4.012
	17	1.840	4.010
	S.L.*	1.8**	4.**
6	N-1	1.8**	4.5**
	N-2	1.8**	4.5**
	N-3	1.8**	4.5**
7	11	1.846	4.013
	12	1.830	4.006
	13	1.840	4.018

* Composed of two semi-logs

** Values only known to two significant figures

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TABLE II
AVERAGE DENSITY OF BERYLLIUM OXIDE SLABS

Slab No.	Thickness Inches	Average Density gm/cm ³
1	9	2.90
2	4	2.93
3	4	2.95
5	4	2.91

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MATCHED WINDOW DETECTOR ASSEMBLY
TYPE 32MB32/A

HARSHAW CHEMICAL COMPANY
Cleveland, Ohio

A diagram of the collimator and shield is shown in Figure 9. Measurements behind various thicknesses of beryllium oxide were made with a steel collimator. In order to reduce the number of capture gammas originating in the collimator, it was replaced by an aluminum one. Measurements behind various thicknesses of beryllium and lithium hydride were made with the aluminum collimator. For all the above measurements, there was approximately 1/8 inch of water between the end of the collimator and the test material.

The reported data are corrected for background counts and un-collimated counts. This was achieved by measuring the total counting rates and background counting rates with and without a 6-inch-thick lead brick over the end of the collimator. The difference for the total counting rate may be expressed as

$$C_{CT} = C_{TT} - C_{UT} \text{ where}$$

C_{CT} is the counting rate for gamma rays traversing the collimator,

C_{TT} is the measured counting rate without the lead brick, and

C_{UT} is the measured counting rate with the lead brick placed over the collimator.

The measurements were repeated with the shutdown curtain in front of the source plate. This condition gives

$$C_{CB} = C_{TB} - C_{UB} \text{ where}$$

C_{CB} is the background counting rate for gamma rays traversing the collimator,

C_{TB} is the measured background counting rate without the lead brick, and

C_{UB} is the measured background counting rate with the lead brick placed over the collimator.

The counting rate for gamma rays traversing the collimator and corrected for background becomes

$$C = C_{CT} - C_{CB} = C_{TT} + C_{UB} - C_{UT} - C_{TB}.$$

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III. CRYSTAL CALIBRATION

It was planned to use gamma sources of known activity at the end of the collimator to obtain pulse height distributions. From these measurements, the resolution, photofraction, efficiency, and response functions of the crystal spectrometer were to be determined. The contract, however, was terminated before these data were obtained. Preliminary measurements were completed using point sources on the crystal axis at various distances from the crystal face. The collimator and shield were not used for these measurements. In the following paragraphs a tentative method for approximating the response functions for the collimated crystal spectrometer is given.

The resolution of a spectrometer is defined by the equation

$$R = \frac{\Delta E}{E} \quad \text{where}$$

R is the resolution,

E is the energy of the incident photons, and

ΔE is the width of the photopeak at half maximum points.

The value of the resolution depends on the photomultiplier gain variance, the variance in the number of photons in the light pulses, the photon-to-photoelectron transfer, and the transfer variance. The resolution may be approximated by the equation

$$R^2 = \alpha + B/E = (8\ln 2)V_T + \frac{(8\ln 2)(1+V_m)K}{\bar{T}E} \quad \text{where}$$

$\bar{T}$ is the average photon-to-photoelectron transfer,

V_T is the variance in T,

V_m is the photomultiplier gain variance, and

K is the energy absorbed in the crystal per average number of photons produced.

The above equation includes the variance in the number of photons in the light pulses. It is assumed that this distribution is normal. The equation tends to deviate from measured values as the energy of the gamma rays increases.

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Plots of R^2 vs $1/E$ and R vs E are shown in Figures 10 and 11 for the crystal spectrometer before the crystal was damaged and after the crystal was repaired. These measurements were made without the collimator and shield. The collimator should reduce the value of R , since the interaction of the incident photons with the crystal is localized. However, the scattering of photons in the collimator may increase the value of R . Since the resolution was not measured for the collimated spectrometer, it necessitates using the uncollimated measurements for generating response functions.

A diagram showing the relative size of the crystal and collimator is given in Figure 9. Since the diameter of the collimator is small, relative to the diameter of the crystal, the incident intrinsic efficiency may be computed using the equation

$$e(E) = 1 - e^{-M(E)X} \text{ where}$$

$e(E)$ is the efficiency
 $M(E)$ is the linear absorption coefficient, and
 X is the diameter of the crystal.

A table of linear absorption coefficients for thallium activated NaI may be found in reference 4.

The photofraction is defined by the equation

$$P(E) = \frac{\text{Counts in the photo peak}}{\text{Total number of counts}}$$

This quantity is a function of the source detector geometry, size of the crystal, and the energy of the incident photons. Since measurements were not made with the collimated spectrometer, it is suggested the approximate photo fractions be determined from Monte Carlo calculations listed in reference 5. Energy loss spectra are given for a collimated beam with radius of 1.693 inches. Spectra, however, are not given for an 8" x 8" crystal. For a given energy, the photofraction may be approximated by

$$P(E) = f(\sqrt{LR}) \text{ where}$$

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L is the length of the crystal and
R is the radius.

By plotting $[1 - P(E)]$ vs $\sqrt{LR}$ for each energy, approximate values of the photofraction for the 8" x 8" crystal may be determined. Plots of these data are shown in Figure 12. The photofraction as a function of energy, determined by the above method, is shown in Figure 13.

If the reported data are compared with calculated spectra, it is suggested that the calculated spectra be converted to pulse height distributions. In order to make the conversion, the response functions of the crystal spectrometer must be known. The response function is defined by the equation

$$N(E')dE' = \left\{ \int_0^{E_{\max}} AR(E, E')\phi(E)dE \right\} dE' \text{ where}$$

$N(E')dE'$ is the number of counts per unit time falling
in the energy range E' to $E' + dE'$,

$R(E, E')dE'$ is the probability that a gamma ray of energy E
will give a count in the energy range E' to
 $E' + dE'$,

$\phi(E)dE$ is the number of incident gamma rays per unit
time - unit area in the energy range E to
 $E + dE$, and

A is the area of the collimator.

If photons of energy E_0 are incident of the crystal, the normalized energy absorbtion spectrum may be expressed as

$$\eta(E_0, E) = f(E_0, E)dE = e(E_0) \left\{ [1 - p(E_0)] K(E_0, E) \right\} dE$$

for $E \neq E_0$, and

$$\eta(E_0, E_0) = e(E_0)p(E_0) \text{ where}$$

FIGURE 12
INTERPOLATION OF
PHOTOFRACTIONS TO AN
8-Inch by 8-Inch NaI Crystal

K&W SEMI-LOGARITHMIC 359-61
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 70 DIVISIONS

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$f(E_0, E)dE$ is the number of incident gamma rays which loose energy in the range E to $E + dE$,

$\eta(E_0, E_0)$ is the number of incident gamma rays which loose all of their energy in the crystal,

$K(E_0, E)dE$ is the probability that a detected photon will loose energy between E and $E + dE$,

$P(E_0)$ is the photofraction, and

$e(E_0)$ is the incident intrinsic efficiency.

Since the resolution of the scintillation spectrometer is finite, each $\eta(E, E_0)$ will be spread over a Gaussian distribution. This gives for the response function ?

$$R(E_0, E')dE' = \left\{ \frac{e(E_0)[1 - P(E_0)]}{\sqrt{2\pi}} \int_0^{E_0} \frac{K(E, E_0)}{\sigma(E)} \exp \frac{-(E' - E)^2}{2[\sigma(E)]^2} dE \right. \\ \left. + \frac{e(E_0)P(E_0)}{\sqrt{2\pi} \sigma(E_0)} \exp \frac{-(E' - E_0)^2}{2[\sigma(E_0)]^2} \right\} dE' \text{ where}$$

$\frac{1}{\sigma(E)\sqrt{2\pi}} \exp \frac{-(E' - E)^2}{2[\sigma(E)]^2}$ is the normalized Gaussian distribution and

$$\sigma(E) = \frac{ER}{2\sqrt{2\ln 2}} .$$

The integration may be approximated by a summation, but the values of $K(E_0, E)\Delta E$ must be known. Assuming the shape of energy loss spectra to be the same for the 8" by 8" crystal as the tabulated Monte Carlo spectra for a 9" x 8" crystal, the values for $K(E_0, E)$ can be estimated by using the proper normalization factor. For the 9" x 8" crystal we have

$$\frac{N_P}{N} + \frac{\sum N_1}{N} = 1 = P(E) + \frac{\sum N_1}{N} \text{ where}$$

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N is the total number of gamma rays which loose energy in the crystal,

N_p is the number which loose all of their energy in the crystal, and

$\sum N_i$ is the number which loose part of their energy in the crystal.

If the shape of the energy loss spectra is the same as that of the 8" x 8" crystal, one has

$$\frac{N'_p}{N} + b \sum N_i = 1 = P'(E) + b \sum N_i \text{ where}$$

N' is the number which lose all of their energy in the 8" x 8" crystal and

b is the normalization constant.

Solving the two equations for b yields

$$b = \frac{[1 - P'(E)]}{N[1 - P(E)]}.$$

The tabulated Monte Carlo energy loss spectra may be multiplied by b to obtain $K(E_0, E)\Delta E$ for each value of E_0 listed. Using a summation to approximate the integral, we obtain for the response functions

$$R(E_0, E') \approx \sum_{n=1}^{m-1} b \frac{e(E_0)[1 - P(E_0)]}{\sqrt{2\pi}} \frac{F(E_n, E_0)}{\sigma(E_n)} \exp \frac{-(E' - E_n)^2}{2[\sigma(E_n)]^2} \\ + \frac{e(E_0)P(E_0)}{\sqrt{2\pi} \sigma(E_0)} \exp \frac{-(E' - E_0)^2}{2[\sigma(E_0)]^2} \quad \text{where}$$

$F(E_n, E_0)$ is the tabulated energy loss spectra and

m is the total number of energy intervals.

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A method for interpolating to additional values of E_0 is given in reference 8.

In addition to the approximations made in calculating the response functions, scattered radiation in the collimator and shield will also introduce errors in the response functions.

IV. POWER MEASUREMENT

The power of the fission plate was measured by the electro-substitution method. This method consists of matching the temperatures produced by the fission source to those produced by an equivalent electric source. A list of the individual errors and the over-all root-mean-square error are given in Table III.

When measured values are compared with calculated values, it is usually necessary to convert from watts to fissions per second. The energy per fission, neglecting the energy of prompt and fission product decay gamma rays, fission neutrons, and neutrinos, is 173 ± 5 Mev. Using this value we obtain

$$1 \text{ watt} = 1 \frac{\text{Joule}}{\text{sec}} \times \frac{10^7 \text{ ergs}}{\text{Joule}} \times \frac{1 \text{ Mev}}{1.60 \times 10^{-6} \text{ ergs}} \times \frac{1 \text{ fission}}{173 \text{ Mev}}$$

$$= 3.61 \times 10^{10} \frac{\text{fissions}}{\text{sec}}$$

the per cent error in the number of fissions per second is

$$\% \text{ error} = \pm \sqrt{(.8)^2 + \left(\frac{500}{173}\right)^2} \approx \pm 3\%$$

In the future, an attempt will be made to estimate the amount of gamma ray energy absorbed by the plate.

TABLE III
ERRORS IN FISSION-PLATE-POWER CALIBRATION

<u>Source of Error</u>	<u>Per Cent Error</u>
Errors due to difference in extraneous heat losses between fission plate and electrical runs	0.2
Errors due to non-uniform temperature distribution in the plate	0.5
Error in resistance measurement	0.5
Error in current squared	0.2
Error in matching temperature curves	0.25
Root-mean-square error	0.8

V. MEASURED DATA

Graphs of the measured pulse height distributions are shown in the following pages. First high-energy (0 to 9.0 mev) and low-energy (0 to 3.0 mev) measurements behind 4, 9, 13, 17, and 21 inches of beryllium oxide are reported at 0° to the centerline. In addition high-and low-energy data behind 21 inches of beryllium oxide are given for angles of 30° and 45° to the centerline in a horizontal plane. The second series of graphs show high-and low-energy data behind 8-1/2, 12-1/2, 16, 20, 24-1/2, 28-1/2, and 32-1/2 inches of beryllium at 0° to the centerline. The last set of graphs report the high-and low-energy measurements behind 12, 16, 20, 24, 30, and 34 inches of lithium hydride at 0° , 30° , and 45° to the centerline. The fission plate power is included on each graph.

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FIGURE 14
 LOW-ENERGY ANGULAR GAMMA
 SPECTRUM AT 0° BEHIND 4 INCHES
 OF BERYLLIUM OXIDE
 8" x 8" NaI Crystal
 Power 19.5 Watts

Counts per channel - 10 minutes

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FIGURE 16
LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 0°
BEHIND 13 INCHES OF BERYLLIUM OXIDE

8" x 8" NaI Crystal
Power 19.5 Watts

Counts per channel - 10 minutes

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FIGURE 18
LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 0°
BEHIND 21 INCHES OF BERYLLIUM OXIDE

8" x 8" Na Crystal
Power 15. Watts

Counts per channel - 10 minutes

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Counts per channel - 10 minutes

FIGURE 20
HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 0°
BEHIND 9 INCHES OF BERYLLIUM OXIDE
8" x 8" NaI Crystal
Power 19.5 Watts

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FIGURE 23

HIGH-ENERGY ANGULAR GAMMA SPECTRUM
AT 45° BEHIND 21 INCHES OF BERYLLIUM OXIDE

8" x 8" NaI Crystal
Power 21.9 Watts

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Channel Number

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FIGURE 24

LOW-ENERGY ANGULAR GAMMA SPECTRUM
AT 30° BEHIND 21 INCHES OF BERYLLIUM OXIDE

8" x 8" NaI Crystal

Power 21.65 Watts

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FIGURE 25

LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 45°

BEHIND 21 INCHES OF BERYLLIUM OXIDE

8" x 8" NaI Crystal

Power 21.9 Watts

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FIGURE 26

HIGH-ENERGY ANGULAR GAMMA SPECTRUM
AT 30° BEHIND 21 INCHES OF BERYLLIUM OXIDE
8" x 8" NaI Crystal
Power 21.5 Watts

Counts per channel - 10 minutes

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Counts per channel - 10 minutes

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Counts per channel - 10 minutes

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FIGURE 30

LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 0°

BEHIND 20 INCHES OF BERYLLIUM

8" x 8" NaI Crystal

Power 19.73 Watts

Counts per channel - 10 minutes

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Counts per channel - 10 minutes

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Counts per channel - 10 minutes

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Counts per channel - 10 minutes

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FIGURE 40
HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 0°
BEHIND 32-1/2 INCHES OF BERYLLIUM
8" x 8" NaI Crystal
Power 19.53 watts

Counts per channel - 10 minutes

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Counts per Channel - 5 minutes

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FIGURE 45

LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 0° BEHIND
28 INCHES OF LITHIUM HYDRIDE AND 1 INCH OF ALUMINUM

8" x 8" NaI Crystal
Power 16.58 Watts

Counts per Channel - 5 minutes

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Counts per Channel - 5 minutes

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Counts per Channel - 5 minutes

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FIGURE 48
HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 0°
BEHIND 12 INCHES OF LITHIUM HYDRIDE
AND 1/2 INCH OF ALUMINUM
8" x 8" NaI Crystal
Power 17.34 Watts

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Counts per Channel - 5 minutes

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FIGURE 53
 HIGH-ENERGY ANGULAR GAMMA SPECTRUM
 AT 0° BEHIND 30 INCHES OF LITHIUM HYDRIDE
 AND 1-1/2 INCHES OF ALUMINUM

8" x 8" NaI Crystal
 Power 16.32 Watts

Counts per Channel - 5 minutes

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Counts per Channel - 5 minutes

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FIGURE 57

LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 30°
BEHIND 24 INCHES OF LITHIUM HYDRIDE
AND 1-1/2 INCHES OF ALUMINUM
8" x 8" NaI Crystal
Power 13.26 Watts

FIGURE 59

LOW-ENERGY ANGULAR GAMMA SPECTRUM AT 30°
 BEHIND 30 INCHES OF LITHIUM HYDRIDE
 AND 1-1/2 INCHES OF ALUMINUM
 3" x 8" NaI Crystal
 Power 13.11 Watts

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FIGURE 63
HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 30°
BEHIND 24 INCHES OF LITHIUM HYDRIDE
AND 1-1/2 INCHES OF ALUMINUM
8" x 8" NaI Crystal.
Power 13.26 Watts

FIGURE 64

HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 30°
BEHIND 28 INCHES OF LITHIUM HYDRIDE
AND 1 INCH OF ALUMINUM.
8" x 8" NaI Crystal
Power 13.11 Watts

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FIGURE 77
HIGH-ENERGY ANGULAR GAMMA SPECTRUM AT 45°
BEHIND 30 INCHES OF LITHIUM HYDRIDE
AND 1-1/2 INCHES OF ALUMINUM
8" x 8" NaI Crystal
Power 13.26 Watts

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