Measurement and Calculation of Secondary Gamma Rays Resulting from Exposure of Fe, Pb, and H₂O to the ARERR-1 Spectrum

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$5.50; Microfiche \$3.00

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Contract No. W-7405-eng-26

Neutron Physics Division

MEASUREMENT AND CALCULATION OF SECONDARY GAMMA RAYS
RESULTING FROM EXPOSURE OF Fe, Pb, AND H₂O
TO THE ARERR-1* SPECTRUM

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Date Published: August 1977

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ACKNOWLEDGEMENTS

The measurements described herein were performed by A. S. Makarious in partial fulfillment of the requirements for a doctoral degree in neutron physics from the University of Cairo-Egypt. The measurements were performed in Egypt prior to Mr. Makarious' assignment at the Oak Ridge National Laboratory on an IAEA fellowship.

Mr. Makarious is indebted to Professor I. F. Hamouda, Director of the Nuclear Research Center at the Atomic Energy Establishment of Cairo-Egypt, for guidance during the experimental work done at the ARERR-1.

The calculations described herein were performed under the direction of C. E. Clifford* of the ORNL Neutron Physics Division.

Special appreciation is expressed to W. A. Rhoades and R. L. Childs for the use of, for modifications to, and for consultation regarding the inhouse computer code DOT4P1-M. Appreciation is expressed to Edna Whittington and Nancy Smith who typed the final form of this report.

*Presently associated with Radiation Research Associates, Inc., Fort Worth, Texas.

ABSTRACT

Integral experiments were performed to measure the angular distribution of secondary gamma rays produced when various thicknesses of Fe, Pb, and H₂O samples were exposed to bare and to B₄C-filtered neutron beams from the Research Reactor of Egypt. For selected experiments, multigroup coupled neutron-gamma cross sections and a discrete ordinates transport theory code (DOT4P1-M) were used to calculate the secondary gamma rays and the transport of primary gamma rays. Integral comparisons between the calculated and measured spectra were favorable.

Graphical comparisons of the measured flux for various angles of incidence of the neutron beams on the samples, for various angles of exit on the transmitted side of the samples, and for various sample thicknesses are shown. The comparisons show that the angular distribution of secondary gamma rays for the three materials changes slightly with a change in the angle of beam incident on the sample, but increasing the angle between the normal to the sample and the detector by 60° decreases the measured secondary gamma-ray flux up to a factor of two.

An investigation was made to determine the consequences of using single scatter Compton theory versus using discrete ordinates transport calculations to estimate the primary gamma-ray contribution to the measured photon spectra.

CHAPTER I

INTRODUCTION

Shield design studies for nuclear reactors require calculations of the shielding requirements for primary (prompt fission and fission product), secondary, and activation gamma rays and prompt and delayed fission neutrons. Secondary gamma rays are produced throughout the reactor system primarily by the nonfission capture and inelastic scattering neutron-induced reactions. Other reactions, such as the (n,αγ) and the (n,pγ) reactions, can be sources of secondary gamma rays in the system. The importance of secondary gamma rays is illustrated in Fig. 1 by the calculated neutron and gamma-ray dose distributions within a three-cycle W-LiH shield for a SNAP-8 ZrH reference reactor.^{1,2} The shield design objectives were to limit the dose rate on the outer surface of the shield to a maximum value of 1.55×10^3 mrem/hr and to minimize the weight of the spherical shield. Note from the figure that the secondary gamma-ray dose rate dominates at the exit surface of the shield. This example illustrates the importance for shielding design of choosing appropriate high density materials for gamma-ray shielding and low density materials for neutron shielding and for selecting the optimum configuration to achieve design criteria—criteria such as minimum weight, biological dose constraints, etc.

As for any other source of radiation it is important to know the strength, spectral composition, and angular distribution of the secondary gamma rays throughout the system. Calculation of the secondary gamma-ray distribution requires calculation of the neutron spectral composition in the system, the photon production, and the photon transport.

Neutron radiative capture (n,γ) occurs mainly in a compound nucleus, i.e., neutron absorption by a target nucleus produces a compound nucleus which is excited up to an energy equal to the sum of the neutron binding energy in the compound nucleus and the kinetic energy of the captured neutron. Neutron binding energies range from 2.2 MeV in hydrogen up to 11 MeV in silicon. As the kinetic energy of the neutron increases, the total energy available for release increases and the capture gamma-ray spectrum changes. The excitation energy, E*, in the (n,γ) reaction is emitted by gamma quanta whose maximum energy is E*. For neutron energies greater than approximately 10 MeV, the capture cross section becomes so low that capture gamma rays are no longer dominant.²

¹The calculation shown in Fig. 1 was made by R. L. Childs of UCC-ND¹.

Fig. 1. Dose distribution in SNAP-8 reactor with three-cycle W-LiH shield.

If the incident neutron energy exceeds that of the first excited level of a target nucleus, the generation of a neutron with a lower energy is possible. In this case the target nucleus remains in an excited state and passes to the ground state by emitting gamma quanta. This process is called inelastic neutron scattering ($n, n'\gamma$). The de-excitation depends on the spin and parity of the states of the nucleus. Calculations of $(n, n'\gamma)$ cross sections involve detailed calculations requiring specific knowledge of each nucleus. Due to the tedious nature of the calculations and the lack of exact level structure (spin and parity) data, the majority of the $(n, n'\gamma)$ cross sections have been experimentally determined.³

Iron, lead, and water are frequently used materials which are exposed to intense neutron environments in nuclear reactors. Iron is used extensively in structural materials; water is used as a coolant and as a moderator; and all three materials are used as shielding materials. Many investigations have been made of the secondary gamma rays produced from interactions of monoenergetic neutron sources in Fe, Pb, and H₂O samples.⁴⁻¹⁵ The primary objective of this study was to measure the angular distribution of secondary gamma rays resulting from exposure of samples of Fe, Pb, and H₂O to the neutron spectrum from a reactor. Specifically, various thicknesses of the materials of interest were exposed to bare and B₄C-filtered collimated beams from the Research Reactor of Egypt (ARERR-1).¹⁶ A fraction of the secondary gamma rays was then detected by a stilbene crystal whose amplified pulses were recorded by a 100-channel analyzer.

Attempts were made to suppress the primary gamma rays in the ARERR-1 beam by using lead filters. It was found that the lead filters reduced the intensity of the thermal neutrons, a major source of secondary gamma rays, to an unacceptable level. Consequently, the experiments were conducted without lead filters and therefore with primary gamma rays in the ARERR-1 beam. Thus, a secondary objective of this study was to calculate both the primary gamma-ray and secondary gamma-ray contributions to the measured spectra and to correct the measured spectra by removing the primary gamma-ray contribution. Another objective was to test in an integral manner the secondary gamma-ray production cross sections (SGRPXS) used in the calculations by comparing calculated and measured secondary gamma-ray spectra.

CHAPTER II

THE EXPERIMENTS

Experiments were performed to measure the angular and energy distributions of secondary gamma-rays resulting from exposures of infinite extended barriers of various thicknesses of Fe, Pb, and Al canned H₂O to bare and filtered neutron sources. The bare neutron source was a narrow collimated beam (diameter = 1.5 cm.) of neutrons from one of the horizontal channels of the ARERR-1. The reactor is a two-megawatt, water moderated and cooled, reflector type reactor. The reactor core is a cylindrical tank 600 mm. in diameter and 500 mm. high. A cross sectional view is shown in Fig. 2. The core contains 42 fuel baskets. The fuel rods are canned in 1.5 mm. thick Al tubes. A fuel rod, usually 10% enriched uranium, is 10 mm. in diameter and 500 mm. in length. The ARERR-1 lattice is a square type with 17.5 mm. spacing.

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Fig. 2. ARERR-1 core and experimental facilities.

A fast neutron scintillation spectrometer with a double compensation circuit for gamma-ray discrimination was used in the experiments. The choice of this spectrometer was governed by the fact that it is designed to measure either gamma rays or neutrons in a mixed field of both neutrons and gamma rays using a well known method of voltage impulse division. The spectrometer energy resolution varies depending on the gamma-ray energy, E_γ , according to the expression:

$$\eta(\%) = 13 E_\gamma^{-1/2} \quad (1)$$

Dependence of the amplitude of the measured pulse on the energy of gamma quanta within $\pm 2\%$ is linear up to the gamma energy $E_\gamma = 12 \text{ MeV}$.¹⁷

A schematic diagram of the experimental configuration is shown in Fig. 3. By making a gamma-ray discrimination, a stilbene crystal ($\text{C}_{14}\text{H}_{12}$) with a diameter of 30 mm. and a thickness of 20 mm. was used to measure the unfiltered fast neutron spectrum leaking from the reactor at the sample position. Since the threshold energy of the spectrometer is 0.5 MeV, the thermal part of the ARERR-1 spectrum was not measured. The fast neutron spectrum is shown in Fig. 4.

A stilbene crystal with a diameter of 40 mm. and a thickness of 40 mm. was used during the course of secondary gamma-ray angular distribution measurements. A sketch of the detector collimator with the $40 \times 40 \text{ mm.}$ crystal in place is shown in Fig. 5. The measured primary gamma-ray spectrum leaking from the reactor at the sample position is listed in Table 1.

To investigate the dependence of secondary gamma radiation intensity on the Fe, Pb, and H_2O thickness, three different thicknesses of each material were used in the measurements. Iron disk thicknesses were 2, 5, and 10 cm.; Pb disk thicknesses were 3, 5, and 8 cm.; and the water thicknesses were 5, 10, and 20 cm. in a 3-mm.-thick Al container. For a constant slab thickness, the secondary gamma-ray flux increases with the diameter of the disk and then becomes constant at the "infinite disk diameter." Different sample diameters were investigated to determine the infinite diameter for the Fe and Pb. The diameters were found to be 30 cm. for Fe at a distance of 305 cm. between the center of the sample and the crystal and 20 cm. for Pb at a distance of 211 cm. from the center of the slab to the crystal. The Al container for the H_2O had a rectangular cross section of $90 \times 90 \text{ cm.}$ For a sample—crystal separation of 493 cm., the water in the Al container satisfied the infinite geometry criterion. Impurities in the Fe, as determined by chemical analysis, were C (3.0% by weight), Si (0.05%), Mn (1.0%), P (2.0%), and S (0.04%). Impurities in the H_2O were Ca (76 parts per million), Mg (46 ppm), chloride (26 ppm), sulphates SO_4 (41 ppm), and silicates (SiO_2) in an insignificant quantity. Impurities in the Al container for the H_2O were Fe (0.4% by weight), Si (0.3%), Cu (0.07%), Zn (0.05%), Ti (0.03%), and Mn (0.05%). The Pb was 99.99% pure natural Pb.

In the course of the measurements, the sum of the angle between the direction of the beam and the normal to the sample, θ_0 , and the angle between a line from the center of sample to the detector and the normal to the sample, θ , was varied between 30 and 120 degrees. The neutron beam center was directed toward the sample center; the detector center was directed toward the sample center. The center line of the neutron beam, the sample center, and the detector center were on a horizontal plane. The sample was within the solid angle of the detector collimator. Unless otherwise noted, all experimental runs were made with the ARERR-1 operating at full power (2 MW). A fast neutron detector with a ZnS Ag scintillator was used to monitor the reactor power during each run.

The linearity and resolution of the spectrometer was checked with a ^{60}Co source (1.17 and 1.33 MeV photons) and with a Pu-Be source (4.43 MeV photon) before each run. Pulses were recorded with a

Fig. 3. The experimental configuration.

a. UNITS OF THE TSR-II SPECTRUM ARE NEUTRONS /cm²/sec/group.

Fig. 4. ARERR-1 and TSR-II spectra for $E_n \gtrsim 1.5$ MeV.

* B₄C FILTER USED FOR H₂O EXPERIMENTS

Fig. 5. The detector collimator.

Table 1. Primary Gamma-Ray Spectrum Leaking from the ARERR-1 at the Position of the Sample

Energy (MeV)	Number of photons/cm ² /sec
10.19	3.4×10
7.99	4×10^3
6.27	4.9×10^5
4.92	1.04×10^6
3.86	2.3×10^6
3.0	5.2×10^6
2.37	1.68×10^7
1.86	4.0×10^7
1.46	1.4×10^8
1.15	3.4×10^8
0.9	7.0×10^8
0.7	1.16×10^9
0.55	1.26×10^9
0.43	8.4×10^8

100-channel analyzer. The energy width per channel was the same over the whole energy range for the chosen amplifier gain. For each incidence angle θ run, the following three spectra were measured:

1. Effect plus background measurement for the bare ARERR-1 beam. This gave the total yield of secondary gamma radiation due to the capture of thermal neutrons and due to the inelastic scattering of fast neutrons and the radiation due to the transport of primary gamma rays.
2. Effect plus background measurement for the beam after passing through a 1-cm.-thick B₄C filter (2-cm.-diameter enclosed in a sheet of 0.2-mm.-thick Al) positioned at the neutron beam exit. This gave the secondary gamma radiation resulting from the inelastic scattering of fast neutrons with the sample and the radiation due to the transport of the filtered primary gamma rays.
3. A background measurement which was carried out by blocking the beam with a 45-cm.-thick lead filter (5-cm.-diameter) placed on the symmetry axis of the neutron beam between the beam collimator and the sample.

A list of the different sample thicknesses and different θ_0 and θ angles which were used in the measurements is given in Table 2. The time required for taking each spectrum depended on the secondary gamma-ray intensity which in turn depended on the reactor power (constant), sample thickness, and the angles θ_0 and θ . All measurements were corrected for the dead time.

Kolevatonov *et al.*, described a method of using a single-crystal gamma spectrometer with a stilbene crystal for measuring pulse height distribution from secondary gamma rays and a method of converting the pulse height distribution to an energy distribution of gamma quanta.¹⁷ Kolevatonov's conversion method, which was used in this study, is a four step operation as follows:

1. Using linearity calibration data for the detection system, the area of the crystal face, and the running time, the multichannel analyzer data (counts/channel) were converted to an energy distribution of recoil electrons (counts/MeV·cm²·sec). Background was then subtracted from foreground.
2. Numerically differentiating the recoil electron distribution, using tabular data for the efficiency of the detection system and using an assumed rectangular energy distribution of recoil electrons in the

Table 2. Secondary Gamma-Ray Measurements and Calculations

X – measured spectrum

+ – calculated spectrum

Thickness in cm			θ_0	Zero°, θ		30°, θ		50°, θ		70°, θ	
Fe	H ₂ O	Pb		-B ₄ C ^a Filter	+B ₄ C ^b Filter	-B ₄ C Filter	+B ₄ C Filter	-B ₄ C Filter	+B ₄ C Filter	-B ₄ C Filter	+B ₄ C Filter
2	5	3	Zero			X	X	X	X	X	X
5	10	5		+		+		+		+	
10	20	8				X	X	X	X	X	X
5	10	5	30°	+		+		+		+	
				X	X	X	X	X	X	X	X
5	10	5	50°	+		+		+		+	
				X	X	X	X	X	X	X	X
2	5	3	70°	X	X	X	X	X	X		
5	10	5		+		+		+		+	
10	20	8		X	X	X	X	X	X		

^aWithout B₄C filter in ARERR-1 beam.^bWith B₄C filter in ARERR-1 beam.

stilbene crystal, the data from Step 1 were unfolded to give the angular flux at the detector face (photons/MeV·cm²·sec).

- Using a numerical matrix developed by Kolevator *et al.*, the angular flux at the detector face was corrected to compensate for the actual distribution of recoil electrons in the crystal (photons/MeV·cm²·sec).
- The corrected angular flux at the detector face was multiplied by the gamma-ray energy interval between unfolded data points (photons/cm²·sec).

Kolevator's conversion method is described in detail in Appendix A. Also included in the appendix is a listing of the counts-photons conversion matrix, the numerical matrix to compensate for the actual distribution of recoil electrons, and a flux-to-dose conversion table. The conversion process was done with a simple computer program.

The incidence of thermal neutrons at the detector due to neutron scattering in the sample is a function of the material in the sample, θ_0 , θ , and the detector-sample separation. Capture of thermal neutrons by hydrogen in the crystal produces an unwanted contribution having a 2.23 MeV gamma-ray peak in the gamma-ray spectrum. A B₄C filter was positioned in front of the detector during the H₂O experiments to attenuate the thermal neutrons. The B₄C filter was not positioned in front of the detector for the Fe and Pb runs.

To determine the effect of scattered thermal neutrons for the Pb experiments, bare ARERR-1 beam runs were made for $\theta_0 = 10^\circ$ and $\theta_0 = 50^\circ$, both with a B₄C filter in front of the detector and without the filter. The filtered count rate was 15% lower for $\theta_0 = 10^\circ$ and 20% lower for $\theta_0 = 50^\circ$. Therefore, the

unfolded bare beam Pb results were uniformly reduced by 15% for small θ_0 angles (0° and 30°), and were reduced by 20% for the larger angles (50° and 70°). It was found that the unwanted thermal neutron scattering contribution was not present when the B₄C filter was in the ARERR-1 beam. Therefore, no correction was made to the filtered Pb beam runs.

To illustrate the unfolding procedure, experimental data for the 5-cm.-thick Fe and Pb samples and for the 10-cm.-thick H₂O samples are listed in Tables 3-8. Column headings in the tables correspond to the mathematical nomenclature used to describe Kolevatov's conversion method in Appendix A.

Table 3. Experimental Data for 5-cm-Thick Fe Disk for $\theta_0 = 30^\circ$, $\theta = 0^\circ$ (Spectrum No. 48)

Gamma-Ray Energy (MeV)	$N(E_i)^a$ (counts/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$F(E_i)^b$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_i)^c$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_i) \cdot \Delta E^d$ (photons/ $\text{cm}^2 \cdot \text{sec}$)	Dose (E_i) (Rad/sec)
0.465	323.65002	272.97751	347.18319	34.71820	611.04065
0.577	291.53503	829.36312	967.62439	96.76245	2109.47090
0.686	221.25003	738.29553	905.62744	90.56271	2309.34961
0.794	171.70001	551.45971	771.23106	77.12312	2251.99414
0.900	141.40002	520.89135	780.93860	78.09387	2538.05029
1.003	116.94500	569.37463	826.96301	82.69621	2952.25732
1.108	93.61000	390.86785	666.50830	66.65084	2586.05176
1.220	79.55000	402.55999	672.49145	67.24916	2811.01367
1.330	66.97000	365.72992	612.42065	61.24199	2743.64404
1.420	56.95000	612.68457	798.18603	79.81871	3751.47412
1.520	42.11500	509.64044	641.46118	64.14605	3181.64649
1.630	31.15500	472.08551	571.18762	57.22869	2987.31055
1.730	22.18000	337.21728	418.08795	41.80885	2282.75977
1.830	16.44500	258.12176	324.89062	32.48902	1851.87622
1.930	12.48000	233.34967	288.15722	28.81575	1714.53515
2.030	9.23000	203.40466	245.27966	24.52794	1508.46972
2.130	6.66500	170.71020	195.51367	19.55134	1245.42187
2.290	4.68000	97.76132	110.98024	22.19602	1487.13501
2.490	2.69500	60.23116	67.74951	13.54991	962.04284
2.690	1.64750	32.81777	37.79526	7.55904	570.70861
2.890	1.15400	17.17421	20.76326	4.15265	328.05957
3.090	0.92950	12.93176	15.63289	3.12657	259.50610
3.290	0.78000	8.82701	11.30207	2.26041	196.65612
3.490	0.68900	6.96598	9.05790	1.81158	163.94805
3.690	0.62450	8.37475	10.75702	2.15140	202.23196
3.890	0.55500	5.89599	7.27163	1.45432	141.79687
4.090	0.51100	17.62921	17.13807	3.42761	347.90289
4.340	0.39148	11.94028	11.17177	3.35153	355.26257
4.640	0.28227	3.97867	2.61380	0.78413	87.30096
4.950	0.25027	6.10959	4.75279	1.42584	166.34790
5.250	0.20663	1.22391	0.08302	0.02490	3.03861
5.550	0.19890	2.98374	1.51652	0.45495	57.62787
5.850	0.18185	5.31764	3.82076	1.14622	150.92001
6.150	0.15458	3.25099	1.83274	0.54982	75.14266
6.450	0.13969	2.61928	1.37402	0.41220	58.25869
6.750	0.12870	1.71159	0.68636	0.20590	30.20011
7.050	0.12210	3.61815	2.86288	0.85886	130.26126
7.350	0.10936	13.16879	12.77159	3.83148	597.71045
7.750	0.06688	13.87338	13.74196	5.49678	889.10510
8.100	0.01274	1.91520	1.84936	0.73974	124.64718
8.500	0.00602	1.19700	1.17647	0.47058	82.35301
8.900	0.00222	0.76035	0.76035	0.30413	55.50560

^aForeground minus background.

^bEnergy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.

^cEnergy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.

^d $\phi(E_i)$ data times energy interval.

Table 4. Experimental Data for 5-cm-Thick Fe Disk for $\theta_0 = 30^\circ$, $\theta = 50^\circ$

Gamma-Ray Energy (MeV)	$N(E_e)^a$ (counts/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$F(E_j)^b$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_j)^c$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_j) \cdot \Delta E^d$ (photons/ $\text{cm}^2 \cdot \text{sec}$)	Dose (E_j) (Rad/sec)
0.686	1.11780	47.95117	62.32011	6.23200	158.91626
0.794	1.00520	57.72128	64.53961	6.45396	188.45559
0.900	0.91590	28.08830	31.10299	3.11030	101.08471
1.003	0.79300	10.84823	13.21086	1.32108	47.16276
1.108	0.69860	6.66366	8.94338	0.89488	34.72167
1.220	0.66230	4.06400	6.76028	0.67602	28.25799
1.330	0.62600	7.15400	9.29392	0.92939	41.63676
1.420	0.58430	6.59559	8.47098	0.84710	39.81364
1.520	1.11780	5.23590	6.93846	0.69384	34.41478
1.630	1.00520	4.69717	6.16066	0.61606	32.22029
1.730	0.91590	7.22651	8.42225	0.84222	45.98549
1.830	0.79300	6.14544	7.45094	0.74509	42.47036
1.930	0.69860	2.60633	4.29427	0.42942	25.55090
2.030	0.66230	2.87859	4.77629	0.47762	29.37418
2.130	0.62600	3.58620	5.14611	0.51461	32.78076
2.290	0.58430	3.90060	5.08630	1.01726	68.15649
2.490	0.50510	3.69494	4.82255	0.96451	68.48025
2.690	0.44084	2.00431	3.11614	0.62322	47.05377
2.890	0.41070	2.39444	3.35241	0.67048	52.96821
3.090	0.37940	3.35706	4.06887	0.81377	67.54335
3.290	0.34059	3.41148	3.85367	0.77073	67.05394
3.490	0.30542	3.91607	4.10500	0.82100	74.30062
3.690	0.26916	3.54029	3.65595	0.73119	68.73197
3.890	0.23978	2.67329	2.57618	0.51523	50.23564
4.090	0.21983	4.21555	3.80696	0.76139	77.28147
4.340	0.19125	2.85141	2.47470	0.74241	78.69566
4.640	0.16517	1.95328	1.23908	0.37172	41.38557
4.950	0.14946	3.75199	3.01019	0.90305	105.35682
5.250	0.12266	0.83916	0.24421	0.07326	8.93815
5.550	0.11736	0.93800	0.23914	0.07174	9.08733
5.850	0.11200	4.40309	3.63879	1.09163	143.73248
6.150	0.08942	3.62215	2.87462	0.86238	117.85945
6.450	0.07283	1.32036	0.65513	0.19654	27.77771
6.750	0.06729	1.54562	0.99364	0.29809	43.72046
7.050	0.06133	1.68980	1.25444	0.37633	57.07730
7.350	0.05538	4.47949	4.23584	1.27075	198.23733
7.750	0.04093	8.99182	8.90726	3.56290	576.30005
8.100	0.00584	0.64410	0.57854	0.23141	38.99371
8.500	0.00358	0.20790	0.15539	0.06215	10.87784
8.900	0.00292	0.20207	0.17374	0.06949	12.68321

^a Foreground minus background.^b Energy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.^c Energy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.^d $\phi(E_j)$ data times energy interval.

Table 5. Experimental Data for 5-cm-Thick Pb Disk for $\theta_0 = 70^\circ$, $\theta = 0^\circ$

Gamma-Ray Energy (MeV)	$N(E_\gamma)^a$ (counts/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$F(E_\gamma)^b$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_\gamma)^c$ (photons $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_\gamma) \cdot \Delta E^d$ (photons/ $\text{cm}^2 \cdot \text{sec}$)	Dose (E_γ) (Rad/sec)
0.900	3.31500	24.92524	30.94630	3.09463	100.57550
1.003	2.14480	19.65909	23.00072	2.30006	82.11256
1.108	1.33910	10.51951	12.49432	1.24943	48.47798
1.220	0.96070	4.90559	6.55451	0.65545	27.39787
1.330	0.80740	3.18280	4.72429	0.47242	21.16482
1.420	0.72020	3.37420	4.87162	0.48716	22.89663
1.520	0.63850	2.92020	4.43829	0.44382	22.01393
1.630	0.57570	2.14600	3.80600	0.38060	19.90585
1.730	0.53490	2.77888	4.43101	0.44310	24.19335
1.830	0.48764	3.50368	5.35974	0.53597	30.55054
1.930	0.43382	2.78008	5.31180	0.53119	31.60579
2.030	0.39510	0.55510	3.23067	0.32306	19.86862
2.130	0.38810	3.39700	5.27659	0.52765	33.61190
2.290	0.34860	6.56502	7.83272	1.56654	104.95846
2.490	0.21530	3.13317	3.79541	0.75908	53.89495
2.690	0.16081	4.28659	4.66998	0.93399	70.51678
2.890	0.09635	1.42519	1.72923	0.34584	27.32187
3.090	0.07772	0.84424	1.10385	0.22077	18.32395
3.290	0.06796	0.67318	0.88664	0.17732	15.42762
3.490	0.06102	0.82187	0.99930	0.19986	18.08732
3.690	0.05341	0.75915	0.88715	0.17743	16.67851
3.890	0.04711	0.88841	0.97080	0.19416	18.93077
4.090	0.04048	0.96022	0.92936	0.18587	18.86606
4.340	0.03397	0.85170	0.79411	0.23823	25.25288
4.360	0.02618	0.38419	0.30991	0.09297	10.35104
4.950	0.02309	0.39759	0.30936	0.09280	10.82764
5.250	0.02025	0.40849	0.31426	0.09428	11.50217
5.550	0.01767	0.36049	0.25513	0.07634	9.69573
5.850	0.01561	0.44654	0.34043	0.10212	13.44700
6.150	0.01332	0.36461	0.26692	0.08007	10.94412
6.450	0.01165	0.31698	0.23382	0.07014	9.91422
6.750	0.01032	0.34491	0.27869	0.08360	12.26258
7.050	0.00899	0.24423	0.20036	0.06010	9.11651
7.350	0.00813	1.28339	1.26704	0.38011	59.29747
7.750	0.00399	1.02243	1.02243	0.40897	66.15174

^aForeground minus background.^bEnergy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.^cEnergy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.^d $\phi(E_\gamma)$ data times energy interval.

Table 6. Experimental Data for 5-cm-Thick Pb Disk for $\theta_0 = 30^\circ$, $\theta = 50^\circ$

Gamma-Ray Energy (MeV)	$N(E_e)^{a,e}$ (counts/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$F(E_j)^{b,e}$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_j)^{c,e}$ (photons/ $\text{MeV} \cdot \text{cm}^2 \cdot \text{sec}$)	$\phi(E_j) \cdot \Delta E^{d,e}$ (photons/ $\text{cm}^2 \cdot \text{sec}$)	Dose $(E_j)^e$ (Rad/sec)
0.686	4.47860	22.95494	28.76703	2.87670	73.35592
0.794	2.93800	22.52249	25.86504	2.58650	75.52590
0.900	1.70050	12.67775	14.53524	1.45352	47.23955
1.003	1.10530	5.93652	7.40322	0.74032	26.42949
1.108	0.86200	3.73353	5.09180	0.50918	19.75621
1.220	0.72770	2.81280	4.17312	0.41731	17.44367
1.330	0.63980	3.02950	4.22666	0.42266	18.93546
1.420	0.55680	1.81306	3.06916	0.30691	14.42508
1.520	0.51290	2.10180	3.28774	0.32877	16.30719
1.630	0.46770	3.41900	4.55920	0.45592	23.84465
1.730	0.40270	2.12855	3.41500	0.34150	18.64594
1.830	0.36650	1.55588	3.27188	0.32718	18.64973
1.930	0.34260	0.59593	2.64756	0.26475	15.75300
2.030	0.33430	1.44326	3.40895	0.34089	20.96509
2.130	0.31610	6.20060	7.79606	0.77960	49.66093
2.290	0.24400	2.77277	3.80774	0.76154	51.02381
2.490	0.18770	3.76624	4.16922	0.83384	59.20293
2.690	0.12220	3.94345	4.17681	0.83536	63.06984
2.890	0.06290	0.49724	0.73513	0.14702	11.61509
3.090	0.05640	0.33731	0.54855	0.10971	9.10605
3.290	0.05250	0.54701	0.74044	0.14808	12.88365
3.490	0.04686	0.53567	0.69841	0.13968	12.64127
3.690	0.04190	0.65431	0.78552	0.15710	14.76779
3.890	0.03647	0.68473	0.76295	0.15259	14.87765
4.090	0.03136	0.91892	0.89536	0.17907	18.17597
4.340	0.02513	0.69317	0.65411	0.19623	20.80082
4.360	0.01879	0.24991	0.19093	0.05728	6.37738
4.950	0.01678	0.33599	0.27286	0.08186	9.55034
5.250	0.01438	0.21849	0.15161	0.04548	5.54913
5.550	0.01300	0.26949	0.19977	0.05993	7.59131
5.850	0.01146	0.24959	0.18184	0.05455	7.18302
6.150	0.01018	0.27946	0.22101	0.06630	9.06156
6.450	0.00890	0.28838	0.24220	0.07266	10.26936
6.750	0.00769	0.21524	0.18168	0.05450	7.99404
7.050	0.00686	0.79235	0.77513	0.23254	35.26857
7.350	0.00407	0.88969	0.88477	0.26543	41.40766
7.750	0.00120	0.30750	0.30750	0.12299	19.89526

^a Foreground minus background.^b Energy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.^c Energy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.^d $\phi(E_j)$ data times energy interval.^e These data must be divided by 1.75 to normalize the results to a ARERR-1 power of 2 mw.

Table 7. Experimental Data for 10-cm-Thick H₂O "Slab" for $\theta_0 = 50^\circ, \theta = 0^\circ$

Gamma-Ray Energy (MeV)	$N(E_e)^a$ (counts/ MeV · cm ² · sec)	$F(E_j)^b$ (photons/ MeV · cm · sec)	$\phi(E_j)^c$ (photons/ MeV · cm ² · sec)	$\phi(E_j) \cdot \Delta E^d$ (photons/ cm ² · sec)	Dose (E_j) (Rad/sec)
0.465	67.69700	187.92650	222.97392	22.29739	392.43410
0.577	45.58800	184.43400	230.09840	23.00984	501.61452
0.686	29.95800	156.45000	202.09480	20.20948	515.34173
0.794	19.45800	123.55980	166.55873	16.65587	486.35148
0.900	12.66900	131.95350	158.19888	15.81969	514.13986
1.003	6.47400	77.10400	92.22296	9.22230	329.23595
1.108	3.31400	49.65080	56.00526	5.60053	216.30041
1.220	1.52800	21.72800	24.46907	2.44691	102.28070
1.330	0.84900	9.41700	10.87573	1.08757	48.72327
1.420	0.59100	4.17130	5.51937	0.55194	25.94102
1.520	0.49000	1.30200	3.00263	0.30026	14.89303
1.630	0.46200	0.56808	2.84490	0.28449	14.87882
1.730	0.45120	0.42336	3.47549	0.34755	18.97615
1.830	0.44400	0.26040	4.17692	0.41769	23.80842
1.930	0.44000	1.00520	5.91657	0.59166	35.20359
2.030	0.45400	3.09270	9.09464	0.90946	55.93201
2.130	0.49300	6.83700	11.65530	1.16553	74.24426
2.290	0.57250	7.26438	8.63287	1.72657	115.68045
2.490	0.42500	22.59750	22.68688	4.53758	322.15364
2.690	0.03200	2.12800	2.12800	0.42560	32.13280

^aForeground minus background.^bEnergy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.^cEnergy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.^d $\phi(E_j)$ data times energy interval.Table 8. Experimental Data for 10-cm-Thick H₂O "Slab" for $\theta_0 = 30^\circ, \theta = 50^\circ$

Gamma-Ray Energy (MeV)	$N(E_e)^a$ (counts/ MeV · cm ² · sec)	$F(E_j)^b$ (photons/ MeV · cm · sec)	$\phi(E_j)^c$ (photons/ MeV · cm ² · sec)	$\phi(E_j) \cdot \Delta E^d$ (photons/ cm ² · sec)	Dose (E_j) (Rad/sec)
0.465	38.00625	220.19038	239.07825	23.90783	420.77772
0.577	12.10150	112.86405	116.86179	11.68618	254.75871
0.686	2.53675	22.34330	23.13871	2.31387	59.00372
0.794	1.03720	7.78651	7.60486	0.76049	22.20619
0.900	0.60937	4.27640	3.53940	0.35394	11.50305
1.003	0.40860	0.45384	0.06153	0.00615	0.21968
1.108	0.39000	0.41700	0.38470	0.03847	1.49262
1.220	0.37500	0.32000	0.68372	0.06837	2.85793
1.330	0.36300	0.18250	1.00077	0.10008	4.48346
1.420	0.36000	0.08260	1.41628	0.14163	6.65652
1.520	0.35800	0.09300	1.99876	0.19988	9.91386
1.630	0.36000	0.10520	2.71831	0.27183	14.21675
1.730	0.36200	0.17640	3.60138	0.36014	19.66355
1.830	0.36500	0.97650	5.25470	0.52547	29.95178
1.930	0.38000	1.99748	7.25321	0.72532	43.15663
2.030	0.40782	4.36467	10.37498	1.03750	63.80612
2.130	0.46286	8.69288	13.03534	1.30353	83.03513
2.290	0.56394	9.55549	10.49138	2.09828	140.58453
2.490	0.36992	21.27040	21.27040	4.25408	302.03968

^aForeground minus background.^bEnergy distribution of measured photons based on a rectangular distribution of recoil electrons in the stilbene crystal.^cEnergy distribution of measured photons after correcting for "actual" distribution of recoil electrons in the stilbene crystal.^d $\phi(E_j)$ data times energy interval.

CHAPTER III

THE CALCULATIONS

For the selected experiments identified in Table 2, calculations were made of the gamma-ray flux at the detector due to the primary gamma rays striking the sample and due to secondary gamma rays produced in the sample as a result of the bare neutron beam. The calculations were made using multigroup (energy) neutron-gamma cross sections in a special one-dimensional version of a two-dimensional discrete ordinates transport code.

For the Fe disks, the samples were assumed to be composed of Fe, C, Si, and Mn with the following number densities:

Material	Number Density (atoms/bn·cm)
Fe	0.081200
C	0.011800
Mn	0.000862
Si	0.000101

The composition of the H₂O samples was assumed to be as follows:

Material	Number Density (atoms/bn·cm)	Remarks
H	0.06688	
O	0.03344	
Al	0.06020	Container

For the Pb calculations, the disks were assumed to be composed of natural Pb with a number density of 0.032948 atoms/bn·cm.

Multigroup cross sections used in this study were taken from an undocumented, ANISN-formatted^a cross-section library.¹⁸ Due to the importance of the cross sections, the processing of the multigroup data is described here.^b

Starting point for the processing of the multigroup cross sections was the evaluated ENDF/B-formatted data listed in Table 9. The H (MAT 1269), Mn (MAT 1197), Fe (MAT 1192), and Pb (MAT 1288) ENDF/B-formatted data were obtained from the ENDF/B-IV library which is available from the Brookhaven National Laboratory (BNL).¹⁹ Carbon (MAT 65) data was obtained from an undocumented preliminary ENDF/B-III evaluation obtained from the Los Alamos Scientific Laboratory (LASL). Oxygen (MAT 4134), Al (MAT 4135), Pb (MAT 4136), and Si (MAT 4151) data were obtained from the Defense Nuclear Agency (DNA) library.²⁰

Carbon, O, Al, Pb, and Si ENDF/B-formatted data were first processed into flux-averaged 231 neutron energy group, 25 gamma-ray energy group (231n-25γ) cross sections with the AMPX modular code system.²¹ The assumed flux shapes used in the neutron and photon production fine-group averaging procedure are listed in Table 10. A flat flux was used in the photon interaction cross-section

^aANISN library format is described on Page 23 of Ref. 22.

^bThe multigroup processing was previously done by WEF for other projects unrelated to this study.

Table 9. Selected Data from the 51n-25 γ ANISN-Formatted Cross Section Library

Nuclide	Evaluated Library	MAT Number	Assumed Flux Shape ^a	Fine-to-Broad Group Collapsing Function ^b	51n-25 γ Library Identification Numbers ^{c,d}	Remarks
H	ENDF/B-IV	1269 ^e	1/E-Max	N/A	358-361	
C	Preliminary ENDF/B-III	65	1/E σ_T -Max	A	105-108	
O	DNA	4134, mod 2	FISS-1/E-Max	B	1-4	
Al	DNA	4135, mod 2	1/E σ_T -Max	A	49-52	Photon production cross sections include the 1.78 MeV activation gamma ray
Si	DNA	4151, mod 2	1/E σ_T -Max	A	129-132	
Mn	ENDF/B-IV	1197	1/E-Max	N/A	341-344	
Fe	ENDF/B-IV	1192	1/E σ_T -Max	N/A	337-340	
Pb	ENDF/B-IV	1288	FISS-1/E-Max	N/A	404-407	
Pb	DNA	4136, mod 4	1/E σ_T	A	69-72	

^aFlux shapes that were used in the XLACS and LAPHNGAS fine-group averaging procedure for the neutron and photon production data. See Table 10 for a definition of the code used to identify the flux and the energy ranges of the various spectra.

^bThe following code is used to identify the fine-to-broad group collapsing function:

Code	Collapsing Function
A	Maxwellian spectrum (at 300°K) for $1.0 \times 10^{-5} \leq E_n \leq 0.1264$ eV; 1/E spectrum for $E_n > 0.1264$ eV
B	LMFBR core spectrum
N/A	No fine-to-broad group collapse

^cSee Ref. 18.

^dP₀ - P₃ components.

^eWater bound hydrogen data were "fudged" into the lowest neutron group by assuming values of $\sigma_a = 45.0$ b and $\sigma_{n,\gamma} = 0.266$ b.

Table 10. Assumed Flux Shapes for Neutron and Photon Production Averaging Procedure^a

Identification	Energy Range (eV)	Spectrum
• 1/E – Max Spectrum	$1.49180 \times 10^7 - 0.1264$ $0.1264 - 1.0 \times 10^{-5}$	1/E Maxwellian (300°K)
• $1/E\sigma_T$ – Max Spectrum	$1.49180 \times 10^7 - 0.1264$ $0.1264 - 1.0 \times 10^{-5}$	$1/E\sigma_T$ where σ_T was the total cross section for the nuclide of interest Maxwellian (300°K)
• Fiss – 1/E – Max Spectrum	$1.49180 \times 10^7 - 67.4 \times 10^4$ $67.4 \times 10^4 - 0.1264$ $0.1264 - 1.0 \times 10^{-5}$	Fission 1/E Maxwellian (300°K)

^aSpectra described in Ref. 21.

averaging calculation. The fine-group neutron structure and the gamma-ray group structure are listed in Tables 11 and 12, respectively. The XLACS, LAPHNGAS, SMUG, CHOX, and NITAWL modules of the AMPX system were used to calculate the ^{231}In -25 γ ANISN-formatted cross sections. A short description of each of the AMPX modules and each stand-alone code used in this study is included in Appendix B. A flowchart of the calculational procedure is shown in Fig. 6.

Using the spectra identified in Table 10, the neutron and photon production components of the ^{231}In -25 γ cross sections were collapsed with ANISN²² to a 51 neutron group, 25 gamma-ray group structure (51n-25 γ). The 51n group structure is listed in Table 13. All calculations involving neutrons described hereinafter were made with the 51n group structure.

The AMPX system was used to process the H, Mn, Fe, and Pb ENDF/B-formatted data directly into the 51n-25 γ group structure. Assumed flux shapes used in the neutron and photon production fine-group averaging procedure are identified in Table 10.

It was noted that the characteristics of the ARERR-1 were similar to ORNL's TSR-II reactor²³, i.e., both were water moderated reactors with the same reflector thickness. Because of the similarities, the full neutron-energy-range TSR-II spectrum was assumed applicable to the ARERR-1. A multigroup representation of the TSR-II spectrum in the 51n group structure is listed in Table 13. The spectrum was obtained by "grouping" the 100 group spectrum listed in Table I of Ref. 23 into the 51n group structure and multiplying by a correction factor of 0.658^a to convert the TSR-II source to a per watt basis.

The measured ARERR-1 primary gamma-ray spectrum (see Table I) was put in the 25 gamma-ray group structure as listed in Table 14. Since low energy gamma-rays are not important in this study, it was assumed that the primary gamma-ray spectrum was zero for $E_\gamma \leq 0.34029$ MeV.

The multigroup representations of TSR-II neutron beam or the primary gamma-ray beam and the coupled cross sections were input to an inhouse version (DOT4P1-M) of the two-dimensional discrete ordinates transport code DOT²⁴ to calculate the gamma-ray angular flux emanating from the detector side of the sample. DOT4P1-M can process a series of one-dimensional discrete ordinates transport calculations in a single calculation. Four different incident TSR-II neutron or primary gamma-ray beams, incident in a specific θ_0 angle, were modeled in each DOT4P1-M P₃ calculation. Tables of the calculated angular flux (photons/cm²·sec·unit weight) on the detector side of the sample in the θ angles of interest are included in Appendix C.

^aRe. R. E. Maerker, private communication.

Table 11. Neutron Fine-Group (231n) Energy Structure

Group Number	Upper Energy (eV)	Group Number	Upper Energy (eV)	Group Number	Upper Energy (eV)
1	1.49180E 07 ^a	78	1.61220E 06	155	3.51750E 04
2	1.45500E 07	79	1.57240E 06	156	3.43070E 04
3	1.41910E 07	80	1.53350E 06	157	3.18280E 04
4	1.38400E 07	81	1.49570E 06	158	2.80880E 04
5	1.34990E 07	82	1.42270E 06	159	2.60580E 04
6	1.31650E 07	83	1.35340E 06	160	2.47880E 04
7	1.28400E 07	84	1.28730E 06	161	2.41760E 04
8	1.25230E 07	85	1.22460E 06	162	2.35790E 04
9	1.22140E 07	86	1.19430E 06	163	2.18750E 04
10	1.19120E 07	87	1.16480E 06	164	2.13850E 04
11	1.16180E 07	88	1.10800E 06	165	1.93050E 04
12	1.13310E 07	89	1.05400E 06	166	1.70360E 04
13	1.10520E 07	90	1.00260E 06	167	1.50340E 04
14	1.07790E 07	91	9.77830E 05	168	1.52680E 04
15	1.05130E 07	92	9.61640E 05	169	1.17090E 04
16	1.02530E 07	93	9.53690E 05	170	1.03330E 04
17	1.00000E 07	94	9.07180E 05	171	9.11879E 03
18	9.75310E 06	95	8.62940E 05	172	8.04730E 03
19	9.51230E 06	96	8.20850E 05	173	7.10170E 03
20	9.27740E 06	97	7.80820E 05	174	6.26730E 03
21	9.04840E 06	98	7.42740E 05	175	5.53080E 03
22	8.82500E 06	99	7.06510E 05	176	5.00450E 03
23	8.60710E 06	100	6.72060E 05	177	4.52830E 03
24	8.39460E 06	101	6.39280E 05	178	4.30740E 03
25	8.18730E 06	102	6.08100E 05	179	4.09730E 03
28	7.98520E 06	103	5.78440E 05	180	3.70740E 03
27	7.78800E 06	104	5.50230E 05	181	3.35460E 03
28	7.59570E 06	105	5.36630E 05	182	3.03510E 03
29	7.40820E 06	106	5.23400E 05	183	2.86350E 03
30	7.22530E 06	107	5.10470E 05	184	2.74850E 03
31	7.04690E 06	108	4.97870E 05	185	2.61260E 03
32	6.87290E 06	109	4.73590E 05	186	2.48520E 03
33	6.70320E 06	110	4.50490E 05	187	2.24870E 03
34	6.64780E 06	111	4.28520E 05	188	2.03470E 03
35	6.59240E 06	112	4.07620E 05	189	1.84110E 03
36	6.53770E 06	113	3.87740E 05	190	1.66590E 03
37	6.37630E 06	114	3.68830E 05	191	1.58460E 03
38	6.21890E 06	115	3.50840E 05	192	1.50730E 03
39	6.06530E 06	116	3.33730E 05	193	1.36390E 03
40	5.91560E 06	117	3.17460E 05	194	1.23410E 03
41	5.76950E 06	118	3.09620E 05	195	9.61120E 02
42	5.48810E 06	119	3.01970E 05	196	7.48520E 02
43	5.22050E 06	120	2.94520E 05	197	5.82950E 02
44	4.96590E 06	121	2.87250E 05	198	4.54000E 02
45	4.84320E 06	122	2.80150E 05	199	3.53580E 02
46	4.72370E 06	123	2.73240E 05	200	2.75360E 02
47	4.60700E 06	124	2.59910E 05	201	2.14450E 02
48	4.49330E 06	125	2.47240E 05	202	1.67020E 02
49	4.27410E 06	126	2.35180E 05	203	1.30070E 02
50	4.06570E 06	127	2.23710E 05	204	1.01300E 02
51	3.86740E 06	128	2.12800E 05	205	7.88930E 01
52	3.67880E 06	129	2.02420E 05	206	6.14420E 01
53	3.49940E 06	130	1.92550E 05	207	4.78510E 01
54	3.32870E 06	131	1.83160E 05	208	3.72670E 01
55	3.24650E 06	132	1.74220E 05	209	2.90230E 01
56	3.16640E 06	133	1.69020E 05	210	2.26030E 01

Table 11. (continued)

Group Number	Upper Energy (eV)	Group Number	Upper Energy (eV)	Group Number	Upper Energy (eV)
57	3.08820E 06	134	1.55730E 05	211	1.76030E 01
58	3.01190E 06	135	1.61630E 05	212	1.37100E 01
59	2.86500E 06	136	1.57640E 05	213	1.06770E 01
60	2.72530E 06	137	1.49960E 05	214	8.31530E 00
61	2.59240E 06	138	1.42840E 05	215	6.47600E 00
62	2.46600E 06	139	1.35690E 05	216	5.04350E 00
63	2.42510E 06	140	1.29070E 05	217	3.92790E 00
64	2.38520E 06	141	1.22770E 05	218	3.05900E 00
65	2.36530E 06	142	1.16790E 05	219	2.38240E 00
66	2.34570E 06	143	1.11090E 05	220	1.85540E 00
67	2.30690E 06	144	9.80370E 04	221	1.44500E 00
68	2.26690E 06	145	8.65170E 04	222	1.12540E 00
69	2.23130E 06	146	7.63510E 04	223	8.76420E-01
70	2.12250E 06	147	6.73790E 04	224	8.33880E-01
71	2.01900E 06	148	6.25110E 04	225	6.82560E-01
72	1.96910E 06	149	5.94620E 04	226	6.25060E-01
73	1.92050E 06	150	5.65620E 04	227	5.31580E-01
74	1.87310E 06	151	5.24750E 04	228	4.13990E-01
75	1.82680E 06	152	4.63090E 04	229	3.00000E-01
76	1.73770E 06	153	4.08680E 04	230	2.00000E-01
77	1.65300E 06	154	3.60660E 04	231 ^b	1.00000E-01

^aRead 1.49180×10^7 .^bBottom energy of group 231 is 1.0×10^{-5} eV.Table 12. Gamma-Ray
Energy Group Structure

Group Number	Upper Energy (eV)
1	1.30000E 07 ^b
2	1.01970E 07
3	7.99880E 06
4	6.27370E 06
5	4.92100E 06
6	3.85990E 06
7	3.02770E 06
8	2.37400E 06
9	1.86260E 06
10	1.46110E 06
11	1.14610E 06
12	8.98980E 05
13	7.05130E 05
14	5.53090E 05
15	4.33830E 05
16	3.40290E 05
17	2.66920E 05
18	2.09370E 05
19	1.64220E 05
20	1.28810E 05
21	1.01040E 05
22	7.92520E 04
23	6.21640E 04
24	4.87600E 04
25	3.82470E 04 ^b

^aRead 1.30000×10^7 .^bBottom energy of group 25 is 3.0×10^4 eV.

Fig. 6. Calculational Sequence.

Table 13. Multigroup TSR-II Neutron Spectrum

Group Number	Upper Energy (eV)	Neutron Intensity (neutrons/cm ² /min/watt)	Group Number	Upper Energy (eV)	Neutron Intensity (neutrons/cm ² /min/watt)
1	1.491825+7 ^a	30	27	5.247533+4	2132
2	1.221403+7	179	28	4.086781+4	1987
3	1.000000+7	564	29	3.182790+4	1849
4	8.187308+6	1461	30	2.478759+4	1743
5	6.703202+6	3062	31	1.930459+4	1632
6	5.488117+6	4503	32	1.503443+4	1566
7	4.493294+6	6118	33	7.101762+3	1493
8	3.678799+6	6671	34	4.307434+3	1401
9	3.011945+6	8977	35	3.354635+3	1336
10	2.465972+6	8648	36	2.612593+3	1289
11	2.018968+6	7069	37	2.034689+3	1250
12	1.652991+6	5395	38	1.584618+3	1197
13	1.353355+6	3720	39	1.234101+3	1184
14	1.108033+6	2951	40	9.611191+2	1184
15	9.071815+5	3007	41	4.540005+2	1184
16	7.427376+5	7836	42	2.144546+2	1184
17	6.081016+5	2056	43	1.013012+2	1204
18	4.978716+5	1539	44	4.785130+1	1283
19	4.076229+5	1543	45	2.260335+1	1362
20	3.337334+5	1437	46	1.067707+1	1362
21	2.732379+5	1179	47	5.043490	1421
22	2.237083+5	1120	48	2.382376	1592
23	1.831569+5	1100	49	1.125354	1918
24	1.499562+5	1041	50	4.14001-1	6376
25	1.227736+5	1756	51 ^b	9.999996-2	57384
26	8.651713+4	2316			

^aRead 1.491825 × 10⁷.^bBottom energy of group 51 is 1.0 × 10⁻⁵ eV.

Table 14. Multigroup ARERR-1 Primary Gamma-Ray Spectrum

Gamma-Ray Group	Coupled Group	Upper Energy (MeV)	Number of Photons/cm ² /sec
1	52	13.0000	0.0
2	53	10.1970	3.4 × 10
3	54	7.9983	4 × 10 ³
4	55	6.2737	4.9 × 10 ⁵
5	56	4.9210	1.04 × 10 ⁶
6	57	3.8599	2.3 × 10 ⁶
7	58	3.0277	5.2 × 10 ⁶
8	59	2.3748	1.68 × 10 ⁷
9	60	1.8628	4.0 × 10 ⁷
10	61	1.4611	1.4 × 10 ⁸
11	62	1.1461	3.4 × 10 ⁸
12	63	0.89896	7.0 × 10 ⁸
13	64	0.70513	1.16 × 10 ⁹
14	65	0.55309	1.26 × 10 ⁹
15	66	0.43383	8.4 × 10 ⁸
16	67	0.34029	0.0
17	68	0.26692	0.0
18	69	0.20938	0.0
19	70	0.16422	0.0
20	71	0.12881	0.0
21	72	0.10104	0.0
22	73	0.079252	0.0
23	74	0.062164	0.0
24	75	0.048760	0.0
25	76	0.038447	0.0

To determine the photon flux at the detector (photons/cm²·sec) for the bare neutron beam calculations, it was necessary to correct the DOT4PI-M calculated angular flux on the detector side of the sample for the geometric attenuation, for the area of the ARERR-1 beam striking the sample, and to normalize the assumed TSR-II spectrum to the ARERR-1 spectrum. To correct and normalize, each value of the calculated angular flux was multiplied by the following factor, F_N :

$$F_N = \frac{A^D \cdot \cos \theta \cdot (\text{wt. for } \theta) \cdot N_F}{4\pi d^2 \cdot A^D \cdot (\text{wt. for } \theta_0)} \cdot A^S \quad (2)$$

where,

A^D = area of the detector face (16 cm²)

d = detector-sample separation (305 cm. for Fe, 211 cm. for Pb, 493 cm. for H₂O)

wt. for θ = discrete ordinates weight for θ (1.0×10^{-8})

wt. for θ_0 = discrete ordinates weight for θ_0 (1.0×10^{-8})

A^S = area of the sample that "sees" the ARERR-1 beam

N_F = term to normalize the neutron flux from the TSR-II spectrum to the ARERR-1 spectrum.

The factor to determine the photon flux at the detector due to the primary gamma-ray beam, F_G , is the same as F_N except that the term to normalize the neutron flux from the TSR-II spectrum to the ARERR-1 spectrum is not included in the numerator of Eq. 2, i.e.,

$$F_G = \frac{A^S \cos \theta}{4\pi d^2} \quad (3)$$

The appropriate F_N or F_G and the angular flux from the data in Appendix C are used in comparisons of calculated and measured results in Chapter IV.

CHAPTER IV

RESULTS AND CONCLUSIONS

An objective of this study was to determine the contribution of the primary gamma rays to the measured spectra. Then, the primary gamma-ray contribution could be subtracted from the measured spectra so that the resulting contribution due to secondary gamma-rays could be analyzed. By examining an experiment and calculation for each of the three types of materials, Fe, Pb, and H₂O, it will be shown that for Fe and Pb all contributions to the measured spectra by photons with energy less than E' can be assumed to be due to primary gamma rays—where E' is the energy of the highest energy photon in the ARERR-1 spectrum after being degraded due to a single Compton scattering in the sample. It is further assumed that removal of the contribution to a measured spectrum below E' leaves the contribution due to neutron interactions in the sample, i.e., the contribution from secondary gamma rays. For H₂O, it will be shown that the Compton single scattering calculation is not adequate and that the primary gamma rays must be calculated.

Quoting from Price, Horton, and Spinney²⁵:

The processes by which gamma rays are attenuated in a shield are well understood; and, provided complicated geometries are avoided, the amount of shielding required to reduce the intensity by a given factor can be calculated to a satisfactory degree of accuracy. Three main processes are involved: pair production, the photoelectric effect, and Compton scattering. The first two depend critically on the atomic number of the absorber, and are particularly important for the heavy elements. The third process involves interactions with orbital electrons; since equal masses of all materials (except hydrogen) contain very roughly the same number of electrons, the contribution made by Compton scattering depends very little on atomic number, and is mainly determined by the mass per unit area of the shield. The energy regions in which the three processes predominate are roughly as follows:

	Photo-Electric Effect	Compton Scattering	Pair Production
Light elements (aluminum)	Below 50 keV	50 keV-15 MeV	Above 15 MeV
Heavy elements (lead)	Below 0.5 MeV	0.5 MeV-5 MeV	Above 5 MeV

From Table 1, p. 8, 99.99% of the gamma rays in the ARERR-1 primary gamma-ray beam have energies less than 5 MeV. Therefore, for this study it is initially assumed that primary gamma rays have only Compton scattering in the samples.

In Compton scattering, a photon of energy E collides with an electron, loses some of its energy and is deflected from its original direction of travel. Assuming the electron to be free and stationary, the relation between photon deflection and energy loss for a single Compton scattering is given by the following equation²⁶:

$$E' = \frac{E}{1 + (E/MC^2)(1 - \cos \psi)} \quad (4)$$

where:

E' is the scattered photon energy,

E is the incident photon energy,

MC^2 is the electron rest energy ($MC^2 = 0.511$ MeV), and

Ψ is the photon deflection angle. For this study, Ψ equals the sum of θ_0 and θ .

A plot showing the relation between E' and E for $\Psi = 30^\circ$, 50° , and 70° is shown in Fig. 7.

Now, consider the 5-cm-thick Fe disk experiment for $\theta_0 = 30^\circ$ and $\theta = 0^\circ$. Recall that the experimentally determined photon flux at the detector for this experiment was given in Table 3, p.10, and that the calculated photon flux at the detector due to primary gamma rays can be obtained by multiplying the appropriate data in Table C2 by the appropriate constant, F_G . Neglecting photons with energies less than ~ 0.7 MeV, the total photon flux at the detector, ϕ_T^M , is 953.6 photons/cm²-sec which is obtained by summing the $\phi(E_i) \cdot \Delta E$ data for $E_\gamma > 0.686$ MeV from Table 3. The calculated primary gamma-ray flux at the detector for $E_\gamma > 0.70513$ MeV, ϕ_p^c , is 920 photons/cm²-sec. The difference, ϕ_T^M minus ϕ_p^c , is assumed to be the measured flux due to neutron interactions in the 5-cm-thick Fe disk, ϕ_s^m , i.e.,

$$\phi_s^m = \phi_T^M - \phi_p^c \quad (5)$$

$$\therefore \phi_s^m = 33.6 \text{ photons/cm}^2\text{-sec}$$

Assuming that calculated primary gamma-ray flux at the detector is not available, an alternate procedure to determine ϕ_s^m can be used. From Table 1, the maximum energy of photons of significant quantity in the ARERR-1 primary gamma-ray spectrum is ~ 9 MeV. Assuming the primary gamma rays have a single Compton scattering in the sample, the curve for $\Psi = 30$ in Fig. 7 shows that the photons will have a maximum energy of 2.69 MeV upon emerging from the detector side of the sample. Assuming that all detected photons with energy $E \leq 2.69$ MeV are primary gamma rays and that all photons of energy $E_\gamma \geq 2.69$ MeV are secondary gamma rays gives a measured ϕ_s^m of 38.3 photons/cm²-sec. Therefore, there is an approximate 12% difference in the measured secondary gamma-ray flux using the calculated primary gamma-ray flux compared with the Compton scattering procedure for determining the primary gamma-ray flux. All measured secondary gamma-ray Fe data for the 2- and 10-cm-thick experiments shown hereinafter were obtained by assuming a single Compton scattering of the primary gamma rays. The measured secondary gamma-ray data for the 5-cm-thick experiments were obtained by subtracting the calculated primary gamma-ray spectrum from the total measured spectrum. It is important to note from the tables of calculated flux in Appendix C that, depending on the sample thickness, there are no primary gamma rays for large values of ψ for $E_\gamma > 0.9$ MeV.

To show the difference between ϕ_p^c and ϕ_p^m for a Pb experiment, consider the 5-cm-thick experiment for $\theta_0 = 70^\circ$ and $\theta = 0^\circ$. Neglecting photons with energies less than 0.9 MeV, the data in Table 5, p.12, gives a total gamma-ray flux at the detector, ϕ_T^m , of 14.88 photons/cm²-sec. Normalizing the calculated flux at the detector due to primary gamma rays for $E_\gamma > 0.899$ MeV (Table C12) gives a ϕ_p^c of 0.88 photons/cm²-sec. Subtracting ϕ_T^m minus ϕ_p^c gives a measured photon flux due to secondary gamma rays of 14.00 photons/cm²-sec.

For E equal to 9 MeV and $\psi = 70^\circ$, the data in Fig. 7 show a maximum E' of 0.75 MeV. Assuming single Compton scattering and subtracting the measured flux for $E_\gamma < 0.90$ MeV from ϕ_T^m leaves a

Fig. 7. Relation between initial and final energy for Compton scattering of photons.

measured photon flux due to secondary gamma rays of 14.88 photons/cm²-sec. This results in an approximate 6% difference in ϕ_s^M when using the calculated ϕ_p^c versus the value obtained using the single scatter Compton theory. The DOT4P1-M calculated results listed in Appendix C show that the primary gamma rays in Pb are negligible for large values of ψ for $E_\gamma > 0.9$ MeV. All measured Pb secondary gamma-ray data shown hereinafter for the 3- and 8-cm-thick Pb experiments were obtained by assuming the single scatter Compton theory. Five-cm-thick Pb results were obtained by using the calculated primary gamma-ray results.

For a final example, consider the 10-cm-thick H₂O sample with $\theta_0 = 50^\circ$ and $\theta = 0^\circ$. Neglecting photons with $E_\gamma < 0.686$ MeV, the experimental data in Table 7, p.14, gives a value for ϕ_T^M of 45.1 photons/cm²-sec. Normalizing and summing the flux for groups 1—12 from the primary gamma-ray calculations (Table C27) gives ϕ_p^c equal to 30.4 photons/cm²-sec. Subtracting, $\phi_T^M - \phi_p^c$, gives a measured photon flux due to secondary gamma rays of 14.7 photons/cm²-sec.

For E equal to 9 MeV and $\psi = 50^\circ$, the data in Fig. 7 shows a maximum E' of ~ 1.22 MeV. Subtracting the measured flux for $E_\gamma < 1.22$ MeV from ϕ_T^M leaves a measured secondary gamma-ray flux of 11.3 photons/cm²-sec. This results in an approximate 30% difference in ϕ_s^M when using calculated ϕ_p^c versus using the single scatter Compton theory. The 30% difference was unacceptable. Consequently, DOT4P1-M primary gamma-ray calculations were made for all H₂O experimental thicknesses and the results were used to obtain all H₂O measured secondary gamma-ray spectra shown hereinafter.

The following section of this chapter is devoted to a summary of the measured angular distribution of secondary gamma rays resulting from exposure of Fe, Pb, and H₂O to the ARERR-1 neutron beam—the primary objective of this study. Where calculations are available, comparisons are made between the calculated and measured angular distribution. For the experiments listed in Table 15, the angular distribution is graphically displayed in Figs. 8–21 by plots of the photon flux and dose versus the angle of photon emergence from the sample, θ . For specific angles of incidence of the ARERR-1 beam on the sample, θ_0 , curves are shown for the bare ARERR-1 neutron beam, for the B₄C-filtered neutron beam, and for the difference between the bare beam and the B₄C-filtered spectra. Note that the primary gamma-ray contribution has been removed from all spectra. The factor in Eq. (2) to normalize the TSR-II spectrum to the ARERR-1 spectrum, NF, was assumed to be 2×10^2 for the calculated results and the area of the samples that “sees” the ARERR-1 beam, A^s , was 3.606 cm².

Table 15. Summary of Plots Showing Angular Distribution of Secondary Gamma Rays

Sample Material	Sample Thickness (cm)	θ_0 Angles (deg.)	Plots				Figure	Type Plots— Flux (F), Dose (D), or Both (B)
			Measured			Calculated Bare Beam		
			Bare Beam	B ₄ C-Filtered Beam	Thermal Beam			
Fe	2	0, 70	✓	✓	✓		8	B
Fe	5	0, 30, 50, 70	✓	✓	✓	✓	9	F
Fe	5	0, 30, 50, 70	✓	✓	✓		10	D
Fe	10	0, 70	✓	✓	✓		11	B
Pb	3	0, 70	✓	✓	✓		12	B
Pb	5	0, 30, 50, 70	✓	✓	✓	✓	13	F
Pb	5	0, 30, 50, 70	✓	✓	✓		14	D
Pb	8	0, 70	✓	✓	✓		15	B
H ₂ O	5	0, 70	✓	✓	✓		16	B
H ₂ O	10	0, 30, 50, 70	✓	✓		✓	17	F
H ₂ O	10	0, 30, 50, 70			✓		18	F
H ₂ O	10	0, 30, 50, 70	✓	✓			19	D
H ₂ O	10	0, 30, 50, 70			✓		20	D
H ₂ O	20	0, 70	✓	✓	✓		21	B

Fig. 8. Measured angular distribution of secondary gamma rays from a 2-cm-thick Fe disk.

Fig. 9. Calculated and measured angular distribution of secondary gamma rays from a 5-cm-thick Fe disk.

Fig. 10. Measured dose due to secondary gamma rays from a 5-cm-thick Fe disk.

Fig. 11. Measured angular distribution of secondary gamma rays from a 10-cm-thick Fe disk.

Fig. 12. Measured angular distribution of secondary gamma rays from a 3-cm-thick Pb disk.

Fig. 13. Calculated and measured angular distribution of secondary gamma rays from a 5-cm-thick Pb disk.

Fig. 14. Measured dose due to secondary gamma rays from a 5-cm-thick Pb disk.

Fig. 15. Measured angular distribution of secondary gamma rays from an 8-cm-thick Pb disk.

Fig. 16. Measured angular distribution of secondary gamma rays from a 5-cm-thick H₂O "Slab".

Fig. 17. Calculated and measured angular distribution of secondary gamma rays from a 10-cm-thick H₂O "Slab".

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Fig. 18. Measured angular distribution of secondary gamma rays from a 10-cm-thick H_2O "Slab" due to a thermal^a neutron beam.

a. Bare minus B_4C filtered neutron beam.

Fig. 19. Measured dose due to secondary gamma rays from a 10-cm-thick H₂O "Slab".

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Fig. 20. Measured dose due to secondary gamma rays from a thermal neutron beam.

Fig. 21. Measured angular distribution of secondary gamma rays from a 20-cm-thick H_2O "Slab".

As the total secondary gamma-ray flux is the summation of the secondary gamma-ray flux due to capture of thermal neutrons and the secondary gamma-ray flux due to inelastic scattering of fast neutrons, putting a B_4C filter in front of the ARERR-1 beam exit permits only fast neutrons to interact with the sample producing secondary gamma rays due to the inelastic scattering of fast neutrons. Therefore, the difference between the bare beam and the B_4C -filtered spectra gives the secondary gamma-rays due to the capture of thermal neutrons in the sample.

Fe Results

It is obvious from the display of the experimental values of the secondary gamma-ray fluxes for the 5-cm-thick iron sample for different angles of θ_0 and θ and the calculated values of secondary gamma-ray fluxes (Fig. 9) that a good agreement exists between the calculated and measured values. The secondary gamma-ray flux increases with increasing sample thickness and then decreases with any further increase of thickness as increasing the thickness beyond a certain limit increases the probability of absorption and energy degradation of the produced secondary gamma rays.

From the figures it is clear that the angular distributions of total secondary gamma-ray fluxes show a slight variation with θ_0 . But it is found that increasing θ by 60° for a particular θ_0 decreases the values of secondary gamma-ray fluxes or dose rates by approximately a factor of two.

The calculated angular flux for the 5-cm-thick Fe experiment with θ_0 and θ equal to 30° and 50° , respectively, is shown in Fig. 22. These are the data listed in Table C6. Note that the spectrum shown in Fig. 22 is the angular flux on the detector side of the Fe sample which results from the incident TSR-II neutron beam. Consequently, the units of the angular flux are (photons $\times$ discrete ordinates weight for θ_0)/(cm²-min-watt-discrete ordinates weight for θ). The weights for θ_0 and θ were the same in the DOT4P1-M calculation. Note that three of the characteristic Fe peaks are present in the multigroup Fe spectrum—the 0.846 MeV inelastic peak and the two capture peaks at 6.02 and 7.64 MeV. Admittedly the gamma-ray energy structure used in the calculations was too broad for a detailed analysis of discrete secondary gamma-ray peaks.

Fig. 22. Calculated secondary gamma-ray angular flux resulting from TSR-II neutron beam incident on 5-cm-thick Fe disk for $\theta_0 = 30^\circ$, $\theta = 50^\circ$.

Pb Results

As shown by the measured Pb data in Tables 5 and 6, pages 12 and 13, respectively, the characteristic 2.62 MeV peak due to the inelastic scattering of fast neutrons and the 7.4 MeV peak due to the capture of thermal neutrons in Pb-208 were observed in the lead measurements. Comparing the measured B₄C filtered results and the "thermal" results for the 3-cm-thick Pb disk experiment with θ_0 equal to 0° (Fig. 12), the contribution to the measured flux of secondary gamma rays due to the inelastic scattering of fast neutrons and due to the capture of thermal neutrons are approximately equal for $30^\circ \leq \theta \leq 70^\circ$. For θ_0 equal to 70° , the spectrum due to the inelastic scattering of fast neutrons is significantly higher than the spectrum due to the capture of thermal neutrons. Conversely, the 8-cm-thick Pb disk results for θ_0 equal to 0° (Fig. 15) show the inelastic scatter and thermal capture spectra to be the same for $30^\circ \leq \theta \leq 50^\circ$ but show the inelastic scatter spectrum to be approximately a factor of two lower for θ equal to 70° . The 8-cm-thick inelastic scattering and thermal capture spectra for θ_0 equal to 70° are approximately equal.

Comparisons of calculated and measured bare beam spectra for the 5-cm-thick Pb disk (Fig. 13) show acceptable agreement for θ_0 equal to 0° , 50° , and 70° . However, there is a factor of approximately 1.5 difference between the calculated and measured spectra for θ_0 equal 30° and for θ equal 0° and 20° . The measured angular distribution of secondary gamma rays due to inelastic scattering of fast neutrons in the 5-cm-thick Pb disk is higher than the spectrum due to the capture of thermal neutrons.

The calculated angular flux of secondary gamma rays on the detector side of the 5-cm-thick Pb disk for θ_0 and θ equal to 30° and 50° , respectively, is shown in Fig. 23. These are the data listed in Table C14.

Fig. 23. Calculated secondary gamma-ray angular flux resulting from TSR-II neutron beam incident on 5-cm-thick Pb disk for $\theta_0 = 30^\circ$, $\theta = 50^\circ$.

H₂O Results

As was noted in Chapter III, a B₄C filter was placed in front of the detector collimator for all the H₂O measurements to attenuate the thermal neutrons. This filter was assumed to attenuate photons of all energies by 4.9%. Therefore, the calculated spectra shown for the 10-cm-thick H₂O "slab" in Fig. 17 have been reduced by the B₄C attenuation factor. Note that there is good agreement between the calculated and measured spectra for θ_0 equal to 0°, 50° and 70°.

As evidenced by the measured 10-cm-thick H₂O slab data in Tables 7 and 8, page 14, the 2.23 MeV hydrogen capture peak was observed in all H₂O measurements—both the bare and the B₄C filtered ARERR-1 beam measurements. The emerging flux of secondary gamma rays on the detector side of the H₂O slabs increases with the increase of water thickness until after a certain thickness the flux decreases with further increase in thickness. The measurements showed that the dependence of secondary gamma-ray production on both θ_0 and θ is weak, i.e., the angular distribution of secondary gamma rays is almost flat over a wide range of θ_0 and θ .

Plots of the angular distribution of secondary gamma rays for the 5-cm-thick H₂O sample (Fig. 16) show that the flux due to the capture of thermal neutrons is higher than the flux due to the inelastic scattering of fast neutrons. For the 10-cm-thick water sample, the spectra due to the inelastic scattering of fast neutrons and due to the capture of thermal neutrons (Figs. 17 and 18, respectively) approach each other. But for the 20-cm-thick H₂O sample, the spectra of secondary gamma rays due to the inelastic scattering of fast neutrons is greater than the spectra due to the capture of thermal neutrons.

The calculated angular flux of secondary gamma rays on the detector side of the 10-cm-thick H₂O "slab" for θ_0 and θ equal to 30° and 50°, respectively, is shown in Fig. 24. These are the data listed in Table C34. As expected, the 2.23 MeV hydrogen capture photon dominates the spectrum.

Fig. 24. Calculated secondary gamma-ray angular flux resulting from TSR-II neutron beam incident on 10-cm-thick H₂O "Slab" for $\theta_0 = 30^\circ$, $\theta = 50^\circ$.

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APPENDIX A

Procedure for Unfolding the Experimental Results

Kolevaton *et al.* described a method of using a single-crystal gamma spectrometer with a stilbene crystal for measuring pulse height distribution from secondary gamma rays and a method of converting the pulse height distribution to an energy distribution of gamma quanta.¹⁷ The following discussion of Kolevaton *et al.*'s conversion method is taken from Ref. 17:

As a first approximation, the energy distribution of recoil electrons in the stilbene crystal can be assumed to be a rectangular distribution of the form $dE/E_{\max}$, where $E_{\max}$ is the maximum energy of the component recoil electron. Conversion of the amplitude distribution of pulses to an energy distribution of gamma quanta can be made by a differentiation method. Since the actual distribution of recoil electrons differs from the assumed rectangular distribution, a correction is made to the energy distribution by using a numerical triangular matrix which is applicable to single-crystal gamma spectrometers. The algorithm for conversion of the amplitude distribution of pulses to an energy distribution of gamma quanta is as follows:

1. The amplitude distribution of pulses, $N(v)$, is converted to an energy distribution of recoil electrons, $N(E_e)$, by the equation

$$N(E_e) = a N(v) \quad (A-1)$$

where, "a" is the experimentally determined channel/McV and E_e is the electron energy.

2. Numerically differentiating the recoil electron distribution, $N(E_e)$, gives an energy distribution of recoil electrons with maximum energy, $F(E)$, or an equal energy distribution of the gamma radiation, $F(E_\gamma)$:

$$F(E_j) = F(E_{\gamma_j}) = \frac{N[E_j + (\Delta E/2)] - N[E_j - (\Delta E/2)]}{\Delta E} \times \frac{E_j K(E_j)}{1 - \exp[-\mu(E_{\gamma_j})d]} \quad (A-2)$$

where, E_j , MeV, is the maximum energy of the component recoil electron in the recording of gamma quanta of energy E_{γ_j} ; ΔE , MeV, is the spacing of the numerical correction matrix; $K(E_j)$ is the correction factor of the effectiveness due to the deviation of the form of the energy distribution of recoil electrons from the $dE/E_{\max}$ distribution; $(1 - \exp[-\mu(E_{\gamma_j})d])$ is the efficiency of the recording of gamma radiation of energy E_j by stilbene crystal of thickness d ; and $\mu(E_{\gamma_j})$ is the total linear coefficient of gamma quanta attenuation in the stilbene crystal.

3. Using a method of correcting the numerical matrix, the energy distribution of recoil electrons with a maximum energy, $\Phi(E)$, or the equal energy dispersion of gamma radiation, $\Phi(E_\gamma)$, is given by

$$\phi(E_j) = \phi(E_{\gamma_j}) = F(E_j) - \sum_{i=j+1}^n \phi(E_i) L(E_i, E_j) \quad (A-3)$$

where,

$$E_{\gamma_j} = \frac{E_j}{2} \left[1 + \left(1 + \frac{1.02}{E_j} \right)^{0.5} \right] \quad (A-4)$$

and $L(E_i, E_j)$ is the element of the corrected numerical matrix. Elements of the correction matrix, obtained by Kolevaton using interpolated and extrapolated data from monoenergetic sources of gamma radiation, are listed in Table A1.

A simple computer program was written to do steps 2 and 3 above. Data for the detector efficiency, the relation between the recoil electron energy and the gamma-ray energy, and a flux-to-dose conversion factor are listed in Table A2.

Table A1. Correction Matrix for 40 × 40 mm Stilbene Crystal to Correct for Actual Energy Dispersion of Recoil Electrons^a

$E_j(\text{MeV})^b$	$E_i(\text{MeV})^c$																																																	
	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.05	2.25	2.45	2.65	2.85	3.05	3.25	3.45	3.65	3.85	4.1	4.4	4.7	5.0	5.3	5.6	5.9	6.2	6.5	6.8	7.1	7.45	7.85	8.25	8.65	9.05	9.45	9.85	10.25	10.65	11.05	11.45	
11.45	0.003 ^d	004	005	006	006	007	008	009	009	010	010	012	013	014	015	016	017	018	020	023	026	028	030	032	035	037	039	042	046	049	054	057	060	061	066	068	069	070	072	075	077	077	079	078	079	076	071	051		
11.05	003	004	005	006	007	008	008	009	010	010	011	012	013	014	015	016	017	018	020	022	025	027	030	032	035	037	039	041	044	047	051	056	058	062	065	067	067	070	071	074	077	078	079	079	075	073	050			
10.65	004	005	006	007	007	008	009	009	010	011	012	013	014	015	016	017	018	019	021	024	026	029	032	034	037	039	042	044	047	050	054	056	059	061	065	066	068	070	073	074	076	077	077	076	073	067	048			
10.25	004	005	006	007	008	008	009	010	010	011	012	013	014	015	016	017	018	019	020	023	025	028	031	033	036	038	041	043	046	050	053	057	058	061	064	067	068	072	073	075	076	075	073	071	065	044				
9.85	004	005	007	007	008	009	009	010	011	012	013	014	015	016	017	018	019	020	022	024	026	029	032	034	037	039	042	044	047	050	054	056	059	062	066	068	072	073	073	072	073	072	066	062	040					
9.45	004	006	007	008	009	009	010	011	011	012	013	014	015	016	018	019	020	022	024	027	030	033	035	038	040	043	045	047	051	053	057	059	063	067	071	072	072	070	070	068	063	057	036							
9.05	005	006	007	008	009	010	010	011	012	013	014	015	016	017	018	019	020	022	025	028	031	034	035	038	041	044	045	047	050	053	056	060	064	069	070	070	069	069	064	060	054	032								
8.65	005	006	008	009	010	010	011	012	013	014	015	016	017	018	019	020	021	023	026	029	032	035	037	039	042	045	046	048	050	054	059	062	066	068	069	067	064	061	057	051	027									
8.25	005	007	008	009	010	011	011	012	013	014	015	016	017	018	020	021	021	023	026	029	032	035	037	040	042	044	045	046	051	054	058	060	064	065	063	060	056	050	045	023										
7.85	006	007	009	010	011	011	012	013	014	015	016	017	018	019	020	021	022	024	027	030	033	035	038	040	042	044	045	047	050	053	056	059	059	061	057	053	046	039	019											
7.45	006	008	009	010	011	012	013	014	015	016	017	018	019	020	021	022	022	025	027	030	033	036	038	040	042	044	045	046	050	051	053	055	054	053	048	039	033	010												
7.1	005	007	008	009	010	010	011	012	012	013	014	015	016	017	018	019	020	021	023	026	029	032	035	037	040	042	044	045	046	051	054	058	060	065	063	060	056	050	045	023										
6.8	005	007	008	009	010	010	011	012	013	014	015	016	017	018	019	020	021	023	026	029	032	035	037	040	042	044	045	046	051	054	058	060	065	063	060	056	050	045	023											
6.5	006	007	008	009	010	010	011	012	012	013	014	015	016	017	018	019	020	021	023	026	029	032	035	037	040	042	044	045	046	051	054	058	060	065	063	060	056	050	045	023										
6.2	006	008	009	010	010	011	011	012	013	013	014	015	016	016	016	017	017	019	021	022	024	025	026	026	026	026	026	026	024	023	021	016	006	-006	-003	0														
5.9	007	008	009	010	011	011	012	013	013	014	015	015	016	016	016	017	017	019	020	021	022	023	023	023	023	023	021	018	015	008	-002	-024	-008	0																
5.6	007	009	010	011	012	012	013	013	014	015	015	016	016	016	017	017	017	018	019	020	020	020	020	019	018	014	009	002	-011	-054	-013	0																		
5.3	008	010	011	012	012	013	013	014	015	015	016	016	017	017	017	016	017	017	017	017	017	017	016	015	013	009	003	-006	-021	-079	-016	0																		
5.0	008	010	011	012	013	014	014	015	016	016	016	017	017	016	016	016	015	014	012	011	009	007	004	001	-005	-012	-027	-053	-129	-024	0																			
4.7	009	011	012	013	014	015	015	016	016	017	017	017	016	016	016	015	014	012	011	009	007	004	001	-005	-012	-027	-053	-129	-024	0																				
4.4	009	012	013	014	015	016	016	017	017	018	018	017	016	015	015	014	012	009	006	003	0	-005	-011	-021	-040	-073	-136	-026	0																					
4.1	010	013	014	016	017	017	018	018	018	017	016	015	015	013	011	008	004	0	-005	-011	-019	-032	-068	-097	-186	-032	0																							
3.8	008	009	010	011	012	012	012	012	012	012	011	010	010	009	007	005	002	-001	-006	-010	-016	-026	-047	-079	-137	-025	0																							
3.6	008	010	011	012	012	012	012	012	012	012	011	010	010	008	007	004	002	-002	-006	-012	-018	-030	-053	-091	-146	-027	0																							
3.45	009	010	011	012	013	013	012	012	011	010	010	080	006	004	002	-002	-006	-012	-020	-032	-060	-102	-154	-029	0																									
3.25	009	011	012	013	013	013	012	012	011	010	008	007	004	002	-003	-007	-012	-020	-033	-064	-113	-162	-031	0																										
3.05	010	012	013	014	014	013	012	011	010	009	007	004	002	-003	-007	-013	-021	-034	-066	-121	-167	-032	0																											
2.85	011	013	014	014	014	013	011	011	009	007	005	002	003	-008	-013	-022	-034	-068	-129	-169	-039	0																												
2.85	012	014	015	015	014	013	011	010	008	005	002	-002	008	014	022	-036	-070	-138	-169	-038	0																													
2.45	013	015	016	015	014	013	011	009	006	003	-001	-007	-013	-024	-037	-074	-149	-174	-042	0																														
2.25	014	016	017	016	015	013	010	008	004	0	-006	012	024	-038	-076	-168	-179	-044	0																															
2.05	016	018	019	018	016	013	010	007	002	-003	-010	-022	-036	-080	-187	-195	051	0																																
1.9	009	010	010	010	008	006	005	002	0	-004	-009	-021	-043	-099	-104	-030	0																																	
1.8	010	010	010	010	008	006	004	002	-002	-007	-020	-042	-095	-104	-031	0																																		
1.7	010	011	011	010	008	006	004	0	-005	-021	-031	-005	-104	-036	0																																			
1.6	010	012	011	010	008	005	002	-002	-019	-040	-092	-103	-043	0																																				
1.5	001	012	011	010	007	004	0005	-017	-038	-089	-102	-052	0																																					
1.4	012	013	012	010	007	004	-013	-035	-085	-101	-071	0																																						
1.3	013	014	012	010	007	-008	-032	-077	-100	-110	0																																							
1.2	013	013	011	009	-003	-026	-065	-099	-141	0																																								
1.1	015	013	011	002	-018	-051	-096	-193	0																																									
1.0	015	012	009	-009	-035	-095	-216	0																																										
0.9	016	012	0	-020	-092	-227	0																																											
0.8	016	011	-009	-082	-226	0																																												
0.7	015	004	-069	-222	0																																													
0.6	013	-053	212	0																																														
0.5	-026	-202	0																																															
0.4	-166	0	0																																															

^aData from Ref. 17.

^bE₁ is the maximum energy of the component recoil electron in the recording of gamma quanta of a specific energy before correction.

cE_i has same meaning as E_j - after correction.

^dAll other numbers in matrix are expressed in thousandths with decimal omitted.

Table A2. Detector Efficiency, Gamma-Ray Energy, and Dose Rate Conversion Factor for
40 × 40 mm Stilbene Crystal^a

Recoil Electron Energy, E _j (MeV)	Detector Efficiency, %	Gamma-Ray Energy (MeV)	Dose Rate Conversion Factor ^b	Recoil Electron Energy, E _j (MeV)	Detector Efficiency, %	Gamma-Ray Energy (MeV)	Dose Rate Conversion Factor ^b
0.30	0.85	0.465	1.76	4.1	32.80	4.340	31.80
0.40	1.18	0.577	2.18	4.4	37.30	4.640	33.40
0.50	1.49	0.686	2.55	4.7	42.00	4.950	35.00
0.60	1.82	0.794	2.92	5.0	47.50	5.250	36.60
0.70	2.13	0.900	3.25	5.3	52.50	5.550	38.00
0.80	2.44	1.003	3.57	5.6	58.50	5.850	39.50
0.90	2.78	1.108	3.88	5.9	65.50	6.150	41.00
1.00	3.20	1.220	4.18	6.2	71.50	6.450	42.40
1.10	3.65	1.330	4.48	6.5	77.80	6.750	44.00
1.20	4.13	1.417	4.70	6.8	85.20	7.050	45.50
1.30	4.65	1.520	4.96	7.1	93.00	7.350	46.80
1.40	5.26	1.630	5.23	7.45	102.50	7.700	64.70
1.50	5.88	1.730	5.46	7.85	114.00	8.100	67.40
1.60	6.51	1.830	5.70	8.25	126.00	8.500	70.00
1.70	7.18	1.930	5.95	8.65	137.00	8.900	73.00
1.80	7.93	2.030	6.15	9.05	152.00	9.300	75.50
1.90	8.60	2.130	6.37	9.45	166.00	9.700	78.00
2.05	9.85	2.290	13.40	9.85	181.00	10.100	80.80
2.25	11.50	2.490	14.20	10.25	197.00	10.500	83.10
2.45	13.30	2.690	15.10	10.65	214.00	10.900	85.50
2.65	15.30	2.890	15.80	11.05	231.00	11.300	88.00
2.85	17.30	3.090	16.60	11.45	254.00	11.700	90.30
3.05	19.40	3.290	17.40				
3.25	21.60	3.490	18.10				
3.45	24.10	3.690	18.80				
3.65	26.80	3.890	19.50				
3.85	29.50	4.090	20.30				

^aData from Ref. 17.

^bFlux (photons/cm² · sec)-to-dose (rads/sec) conversion factor.

APPENDIX B

Summary of AMPX Modules and Other Codes Used in This Study

Following is a list and a brief description of the AMPX modules and other codes used in this study:

1. XLACS—This AMPX module calculates flux-weighted, multigroup neutron cross sections from ENDF/B-formatted data. Data are processed for the full energy range—fast through thermal. Anisotropic processes can be expanded to any order of Legendre polynomial. (See Refs. 21 and 27).
2. LAPHNGAS—This AMPX module calculates flux-weighted, multigroup secondary gamma-ray production cross sections (SGRPXS) or multiplicities from ENDF/B-formatted data. Anisotropic processes can be expanded to any order of Legendre Polynomial. (See Refs. 21, 28, and 29).
3. SMUG—This AMPX module calculates multigroup photon-interaction cross sections with transfer coefficients represented by a Legendre approximation of an arbitrary order. The scattering moments are computed from the Klein-Nishina equation.³⁰ Photoelectric and pair production cross sections are processed from ENDF/B data. (See Refs. 21 and 31).
4. CHOX—This AMPX module prepares the cross sections produced by XLACS, LAPHNGAS, and SMUG for further processing by a subsequent module—NITAWL. (See Ref. 21).
5. NITAWL—This AMPX module does the resonance self-shielding calculations and prepares cross sections into “workable” arrangements such as the format required by the ANISN or DOT code. (See Ref. 21).
6. ANISN—This code solves the one-dimensional Boltzmann transport equation for a slab, cylinder, or sphere by the discrete ordinates method. The code has the capability to perform a group reduction of cross sections by using the flux generated as the solution of the Boltzmann equation. (See Ref. 22).
7. AXMIX—This code prepares macroscopic cross sections from microscopic data and prepares group independent cross-section data to facilitate the DOT4P1-M calculations. (See Ref. 32).
8. DOT4P1-M—This code is an inhouse one-dimensional version of the well-known DOT code.²⁴ The DOT program uses the method of discrete ordinates to solve radiation transport problems in two spatial dimensions.³³ To satisfy the requirements of a separate project, DOT was modified to solve a series of separate one-dimensional problems in a single calculational run. A well-known phenomenon in discrete ordinates calculations of photon transport is negative fluxes due to photon interaction cross section structure contributing to the ingroup scatter term of the Boltzmann equation. Following a study of the effect of the negative fluxes on the primary gamma-ray calculations and after considering various means of negating the negative flux contribution to the calculated angular flux, DOT4P1-M was modified to suppress negative fluxes. This feature was used in all primary gamma-ray calculations.

APPENDIX C

Calculated Angular Flux

Results of the DOT4PI-M calculations of the angular flux on the detector side of the sample are listed in Tables C1–C44. Energy boundaries for the gamma-ray groups are listed in Table 12, p. 19. Units of the angular flux in the following tables due to the TSR-II neutron spectrum listed in Table 13, p. 21, are (photons·wt for θ_0)/(cm²·min·watt·wt for θ). Recall that the factor to normalize the angular flux to photons/cm²·sec, F_N , was given by Eq. (2). Units of the angular flux due to the primary gamma-ray spectrum listed in Table 14, p. 21, are (photons·wt for θ_0)/(cm²·sec·wt for θ). The factor to normalize the angular flux to photons/cm²·sec, F_G , was given by Eq. (3). Contents of the various tables are as follows:

Table	Sample Material	Sample Thickness (cm)	Incident Beam		θ_0 (deg.)	θ 's(deg.)	Remarks
			Neutron	Primary γ -Ray			
C1	Fe	5		X	0.808	0.808,20,50,70	
C2	Fe	5		X	30	0.808,20,50,70	
C3	Fe	5		X	50	0.808,20,50,70	
C4	Fe	5		X	70	0.808,20,50,70	
C5	Fe	5	X		0.808	0.808,20,50,70	
C6	Fe	5	X		30	0.808,20,50,70	
C7	Fe	5	X		50	0.808,20,50,70	
C8	Fe	5	X		70	0.808,20,50,70	
C9	Pb	5		X	0.808	0.808,20,50,70	
C10	Pb	5		X	30	0.808,20,50,70	
C11	Pb	5		X	50	0.808,20,50,70	
C12	Pb	5		X	70	0.808,20,50,70	
C13	Pb	5	X		0.808	0.808,20,50,70	ENDF/B-IV Pb Mat 1288 data
C14	Pb	5	X		30	0.808,20,50,70	ENDF/B-IV Pb Mat 1288 data
C15	Pb	5	X		50	0.808,20,50,70	ENDF/B-IV Pb Mat 1288 data
C16	Pb	5	X		70	0.808,20,50,70	ENDF/B-IV Pb Mat 1288 data
C17	Pb	5	X		0.808	0.808,20,50,70	DNA Mat 4136, Mod 4 data
C18	Pb	5	X		30	0.808,20,50,70	DNA Mat 4136, Mod 4 data
C19	Pb	5	X		50	0.808,20,50,70	DNA Mat 4136, Mod 4 data
C20	Pb	5	X		70	0.808,20,50,70	DNA Mat 4136, Mod 4 data
C21	H ₂ O	5		X	0.808	0.808,20,50,70	
C22	H ₂ O	5		X	30	0.808,20,50,70	
C23	H ₂ O	5		X	50	0.808,20,50,70	
C24	H ₂ O	5		X	70	0.808,20,50,70	
C25	H ₂ O	10		X	0.808	0.808,20,50,70	
C26	H ₂ O	10		X	30	0.808,20,50,70	
C27	H ₂ O	10		X	50	0.808,20,50,70	
C28	H ₂ O	10		X	70	0.808,20,50,70	
C29	H ₂ O	10		X	0.808	0.808,20,50,70	Non-suppressed negative fluxes
C30	H ₂ O	10		X	30	0.808,20,50,70	Non-suppressed negative fluxes
C31	H ₂ O	10		X	50	0.808,20,50,70	Non-suppressed negative fluxes
C32	H ₂ O	10		X	70	0.808,20,50,70	Non-suppressed negative fluxes
C33	H ₂ O	10	X		0.808	0.808,20,50,70	Non-suppressed negative fluxes
C34	H ₂ O	10	X		30	0.808,20,50,70	Non-suppressed negative fluxes
C35	H ₂ O	10	X		50	0.808,20,50,70	Non-suppressed negative fluxes
C36	H ₂ O	10	X		70	0.808,20,50,70	Non-suppressed negative fluxes
C37	H ₂ O	10.6	X		0.808	0.808,20,50,70	No Al can, i.e., H ₂ O "slab"
C38	H ₂ O	10.6	X		30	0.808,20,50,70	No Al can, i.e., H ₂ O "slab"
C39	H ₂ O	10.6	X		50	0.808,20,50,70	No Al can, i.e., H ₂ O "slab"
C40	H ₂ O	10.6	X		70	0.808,20,50,70	No Al can, i.e., H ₂ O "slab"
C41	H ₂ O	20		X	0.808	0.808,20,50,70	
C42	H ₂ O	20		X	30	0.808,20,50,70	
C43	H ₂ O	20		X	50	0.808,20,50,70	
C44	H ₂ O	20		X	70	0.808,20,50,70	

Table C1. Calculated Gamma-Ray Angular Flux for Gamma-Ray Beam Incident at 0.803° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.803°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	5.8855E 00	4.7409E 00	0.0	0.0
3	8.8859E 02	7.1565E 02	0.0	0.0
4	1.3259E 05	1.0663E 05	0.0	0.0
5	5.4233E 05	4.3560E 05	0.0	0.0
6	1.5247E 06	1.2223E 06	0.0	0.0
7	3.9370E 06	3.1429E 06	0.0	0.0
8	1.1910E 07	9.4906E 06	0.0	0.0
9	3.2006E 07	2.5448E 07	0.0	0.0
10	9.8064E 07	7.7789E 07	0.0	0.0
11	2.5037E 08	1.9969E 08	0.0	0.0
12	4.8669E 08	3.9401E 08	9.1802E 07	0.0
13	7.6618E 08	5.2503E 08	1.9917E 08	3.1852E 07
14	8.6269E 08	7.4205E 08	3.2465E 08	1.2013E 08
15	6.1501E 08	5.7804E 08	3.9211E 08	2.2316E 08
16	1.2148E 08	1.4743E 08	2.3095E 08	2.4613E 08
17	9.4204E 07	1.8207E 08	2.2704E 08	2.0505E 08
18	1.5741E 08	1.5240E 08	1.3625E 08	1.2253E 08
19	1.0315E 08	1.0314E 08	9.6127E 07	8.3406E 07
20	5.5485E 07	5.3673E 07	4.5783E 07	3.7453E 07
21	1.2550E 07	1.2280E 07	1.0922E 07	9.3678E 06
22	1.3783E 06	1.3542E 06	1.2302E 06	1.0358E 06
23	6.4799E 04	6.3328E 04	5.5977E 04	4.7908E 04
24	1.0283E 03	1.0085E 03	9.0378E 02	7.7530E 02
25	6.2781E 00	5.1700E 00	5.5854E 00	4.3445E 00

^aAngular flux on detector side of Fe slab.

Table C2. Calculated Gamma-Ray Angular Flux for Gamma-Ray Beam Incident at 30° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.803°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	3.5160E 00	0.0	0.0	0.0
3	5.3152E 02	0.0	0.0	0.0
4	7.9191E 04	0.0	0.0	0.0
5	3.2532E 05	0.0	0.0	0.0
6	9.1723E 05	0.0	0.0	0.0
7	2.3728E 06	0.0	0.0	0.0
8	7.1458E 06	0.0	0.0	0.0
9	1.9270E 07	0.0	0.0	0.0
10	5.8975E 07	0.0	0.0	0.0
11	1.5294E 08	1.7297E 07	0.0	0.0
12	3.0469E 08	9.1669E 07	0.0	0.0
13	4.9387E 08	2.2428E 08	1.8367E 06	0.0
14	6.1698E 08	3.6634E 08	7.9251E 07	1.4566E 07
15	5.3408E 08	4.4533E 08	2.1009E 08	7.9042E 07
16	1.2706E 08	1.6080E 08	2.1203E 08	1.8449E 08
17	9.4204E 07	1.8206E 08	2.2704E 08	2.0505E 08
18	1.4424E 08	1.4505E 08	1.4533E 08	1.4053E 08
19	1.0150E 08	1.0216E 08	9.0949E 07	7.6591E 07
20	5.0478E 07	4.7649E 07	3.9327E 07	3.1893E 07
21	1.1423E 07	1.1164E 07	9.9097E 06	8.4895E 06
22	1.2665E 06	1.2480E 06	1.1368E 06	1.0045E 06
23	5.9174E 04	5.7713E 04	5.0882E 04	4.3523E 04
24	9.3955E 02	9.2200E 02	8.2697E 02	7.1028E 02
25	5.7455E 00	5.6467E 00	5.1203E 00	3.8831E 00

^aAngular flux on detector side of Fe Slab.

Table C3. Calculated Gamma-Ray Angular Flux for Gamma-Ray Beam Incident at 50° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	1.8917E 07	0.0	0.0	0.0
12	8.8576E 07	0.0	0.0	0.0
13	2.1046E 08	3.3853E 07	0.0	0.0
14	3.2926E 08	1.4443E 08	1.5033E 07	0.0
15	3.8705E 08	2.7930E 08	8.5020E 07	2.0129E 07
16	1.1466E 08	1.3681E 08	1.6537E 08	1.2722E 08
17	9.4204E 07	1.8206E 08	2.2704E 08	2.0505E 08
18	1.3008E 08	1.3656E 08	1.3779E 08	1.2727E 08
19	9.1852E 07	8.9469E 07	7.5222E 07	6.1577E 07
20	4.1168E 07	3.8487E 07	3.1594E 07	2.5838E 07
21	9.6134E 06	9.4270E 06	8.3704E 06	7.1670E 06
22	1.0739E 06	1.0580E 06	9.6145E 05	8.4756E 05
23	4.9626E 04	4.8365E 04	4.2615E 04	3.6466E 04
24	7.9016E 02	7.7566E 02	6.9610E 02	5.9746E 02
25	4.8476E 00	4.7668E 00	4.3342E 00	3.1156E 00

^aAngular flux on detector side of Fe slab.

Table C4. Calculated Gamma-Ray Angular Flux for Gamma-Ray Beam Incident at 70° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	2.8966E 05	0.0	0.0	0.0
12	8.3499E 06	0.0	0.0	0.0
13	3.7083E 07	5.3539E 06	0.0	1.4044E 05
14	1.1638E 08	3.7450E 07	9.1837E 05	1.9014E 04
15	1.9615E 08	1.1588E 08	2.4610E 07	4.5851E 06
16	1.1920E 08	1.3762E 08	1.6494E 08	1.2722E 08
17	9.7555E 07	1.8488E 08	2.2733E 08	2.0505E 08
18	1.1267E 08	1.1723E 08	1.0535E 08	8.7772E 07
19	7.2959E 07	6.7635E 07	5.2541E 07	4.1369E 07
20	2.9787E 07	2.7855E 07	2.3122E 07	1.9205E 07
21	7.3316E 06	7.2689E 05	6.5423E 06	5.6403E 06
22	8.2479E 05	8.1079E 05	7.3330E 05	6.4391E 05
23	3.7646E 04	3.6696E 04	3.2369E 04	2.7732E 04
24	6.0260E 02	5.9178E 02	5.3176E 02	4.5562E 02
25	3.7314E 00	3.6746E 00	3.3645E 00	2.0838E 00

^aAngular flux on detector side of Fe slab.

Table C5. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 0.808° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0 ^b	0.0	0.0	0.0
2	8.3349E 02	8.4890E 02	8.8322E 02	7.0331E 02
3	1.1158E 04	1.1377E 04	1.1854E 04	9.3430E 03
4	4.5227E 03	4.7106E 03	5.2627E 03	4.3205E 03
5	3.5053E 03	3.5966E 03	4.2795E 03	3.5834E 03
6	3.8607E 03	4.0720E 03	4.7207E 03	4.0520E 03
7	3.5983E 03	3.3095E 03	4.4398E 03	3.8115E 03
8	3.5081E 03	3.7104E 03	4.3098E 03	3.7746E 03
9	4.2817E 03	4.4456E 03	4.7740E 03	3.8471E 03
10	4.3583E 03	4.4967E 03	4.7791E 03	4.0584E 03
11	4.3166E 03	4.3857E 03	4.4156E 03	3.6915E 03
12	1.1521E 04	1.1600E 04	1.1495E 04	1.0178E 04
13	5.7426E 03	5.7152E 03	5.3130E 03	4.2894E 03
14	1.1114E 04	1.0981E 04	9.8794E 03	7.9493E 03
15	7.8596E 03	7.7248E 03	6.7518E 03	5.2705E 03
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^aAngular flux on detector side of Fe slab.

^bFluxes outside of experimental range of interest were zeroed on purpose.

Table C6. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 30° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0 ^b	0.0	0.0	0.0
2	8.0268E 02	8.1650E 02	8.4091E 02	6.5050E 02
3	1.0701E 04	1.0897E 04	1.1232E 04	8.5741E 03
4	4.3631E 03	4.5402E 03	5.0229E 03	4.0072E 03
5	3.4124E 03	3.5951E 03	4.1211E 03	3.3636E 03
6	3.8410E 03	4.0450E 03	4.6410E 03	3.9036E 03
7	3.6038E 03	3.8086E 03	4.3915E 03	3.6999E 03
8	3.5794E 03	3.7769E 03	4.3357E 03	3.7346E 03
9	4.2756E 03	4.4325E 03	4.7147E 03	3.7385E 03
10	4.4914E 03	4.6248E 03	4.8642E 03	4.0734E 03
11	4.4473E 03	4.5123E 03	4.5059E 03	3.7214E 03
12	1.2291E 04	1.2364E 04	1.2157E 04	1.0614E 04
13	5.9603E 03	5.9321E 03	5.5019E 03	4.4096E 03
14	1.1094E 04	1.0951E 04	9.7977E 03	7.8336E 03
15	7.9358E 03	7.7912E 03	6.7763E 03	5.2730E 03
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^aAngular flux on detector side of Fe slab.

^bFluxes outside of experimental range of interest were zeroed on purpose.

Table C7. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 50° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0 ^b	0.0	0.0	0.0
2	7.4026E 02	7.5131E 02	7.5966E 02	5.5822E 02
3	9.7915E 03	9.9471E 03	1.0052E 04	7.2472E 03
4	4.0341E 03	4.1905E 03	4.5525E 03	3.4482E 03
5	3.2040E 03	3.3688E 03	3.7896E 03	2.9481E 03
6	3.7319E 03	3.9182E 03	4.4022E 03	3.5448E 03
7	3.5389E 03	3.7273E 03	4.2042E 03	3.3960E 03
8	3.6135E 03	3.7963E 03	4.2512E 03	3.5124E 03
9	4.1843E 03	4.3253E 03	4.5061E 03	3.4418E 03
10	4.5983E 03	4.7149E 03	4.8378E 03	3.8964E 03
11	4.5576E 03	4.6079E 03	4.5003E 03	3.5866E 03
12	1.3179E 04	1.3213E 04	1.2694E 04	1.0657E 04
13	6.2440E 03	6.2049E 03	5.5803E 03	4.4452E 03
14	1.0871E 04	1.0707E 04	9.4606E 03	7.4577E 03
15	7.9059E 03	7.7448E 03	6.5677E 03	5.1504E 03
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^aAngular flux on detector side of Fe slab.

^bFluxes outside of experimental range of interest were zeroed on purpose.

Table C8. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 70° on 5-cm-Thick Fe Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0 ^b	0.0	0.0	0.0
2	6.3155E 02	6.3889E 02	6.2914E 02	4.3087E 02
3	8.2643E 03	8.3677E 03	8.2248E 03	5.4950E 03
4	3.4497E 03	3.5742E 03	3.7795E 03	2.6598E 03
5	2.7851E 03	2.9191E 03	3.1853E 03	2.2946E 03
6	3.3390E 03	3.4881E 03	3.7673E 03	2.7602E 03
7	3.2021E 03	3.3532E 03	3.6226E 03	2.6559E 03
8	3.3451E 03	3.4878E 03	3.7078E 03	2.7510E 03
9	3.7903E 03	3.8928E 03	3.8723E 03	2.6986E 03
10	4.2941E 03	4.3627E 03	4.2122E 03	3.0400E 03
11	4.2790E 03	4.2855E 03	3.9359E 03	2.8335E 03
12	1.2533E 04	1.2436E 04	1.1137E 04	8.3839E 03
13	6.1740E 03	6.0852E 03	5.2879E 03	3.8435E 03
14	9.8642E 03	9.6628E 03	8.2927E 03	6.3295E 03
15	7.2247E 03	7.0472E 03	5.9399E 03	4.5004E 03
16	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^aAngular flux on detector side of Fe slab.

^bFluxes outside of experimental range of interest were zeroed on purpose.

Table C9. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 0.808° on 5-cm-Thick Pb Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.5302E 00	1.2136E 00	0.0	0.0
3	2.8391E 02	2.1918E 02	0.0	0.0
4	4.8491E 04	3.7536E 04	0.0	0.0
5	2.1938E 05	1.7015E 05	0.0	0.0
6	6.8340E 05	5.3471E 05	0.0	0.0
7	1.9573E 06	1.5211E 06	0.0	0.0
8	6.2248E 06	4.8261E 06	0.0	0.0
9	1.6307E 07	1.2612E 07	0.0	0.0
10	4.3570E 07	3.5546E 07	0.0	0.0
11	7.9913E 07	6.1656E 07	7.0445E 06	0.0
12	8.9310E 07	6.9704E 07	1.6212E 07	0.0
13	5.4599E 07	4.4295E 07	1.6038E 07	5.5733E 06
14	1.4524E 07	1.3906E 07	1.0904E 07	7.1338E 06
15	4.3802E 05	1.8318E 06	4.4565E 06	4.2909E 06
16	0.0	1.9531E 01	1.0496E 06	1.6690E 06
17	1.6749E 06	1.7363E 06	1.5078E 06	9.6148E 05
18	9.2995E 05	6.3593E 05	3.1502E 05	1.3556E 05
19	2.3009E 04	2.5776E 04	2.6157E 04	2.1261E 04
20	1.4863E 03	1.4976E 03	1.3516E 03	1.0347E 03
21	6.5250E 01	6.5546E 01	6.0962E 01	4.9451E 01
22	4.2431E 00	4.1108E 00	3.5727E 00	2.7343E 00
23	4.7538E-02	4.7435E-02	4.2013E-02	3.0832E-02
24	2.0136E-04	2.0535E-04	2.5094E-04	5.1410E-04
25	3.3852E-07	3.2554E-07	9.9629E-07	6.5162E-07

^aAngular flux on detector side of Pb slab.

Table C10. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 30° on 5-cm-Thick Pb Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	8.4449E-01	0.0	0.0	0.0
3	1.5384E 02	0.0	0.0	0.0
4	2.6501E 04	0.0	0.0	0.0
5	1.2120E 05	0.0	0.0	0.0
6	3.8427E 05	0.0	0.0	0.0
7	1.1020E 06	0.0	0.0	0.0
8	3.5059E 06	0.0	0.0	0.0
9	9.2176E 06	0.0	0.0	0.0
10	2.4503E 07	0.0	0.0	0.0
11	4.5000E 07	8.9042E 06	0.0	0.0
12	5.0920E 07	1.9154E 07	0.0	0.0
13	3.2840E 07	1.8785E 07	3.7124E 06	0.0
14	1.1175E 07	1.0688E 07	5.6736E 06	2.0562E 06
15	1.9552E 06	3.4533E 06	3.4632E 06	2.1473E 06
16	1.7184E 05	6.2674E 05	1.3788E 06	1.6731E 06
17	1.6749E 06	1.7363E 06	1.5078E 06	9.6148E 05
18	9.2995E 05	6.3593E 05	3.1502E 05	1.3556E 05
19	2.3009E 04	2.5776E 04	2.6157E 04	2.1261E 04
20	1.0797E 03	9.7213E 02	7.3028E 02	5.2270E 02
21	5.5394E 01	5.3477E 01	4.7197E 01	3.9855E 01
22	3.4597E 00	3.4549E 00	3.1816E 00	2.7195E 00
23	3.6368E-02	3.6080E-02	3.2057E-02	1.7980E-02
24	1.1132E-04	1.0977E-04	8.6286E-05	1.5650E-04
25	2.1969E-08	7.6520E-07	2.7534E-07	1.0387E-06

^aAngular flux on detector side of Pb slab.

Table C11. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 50° on 5-cm-Thick Pb Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	4.2711E 05	0.0	0.0	0.0
11	7.7878E 06	0.0	0.0	0.0
12	1.4550E 07	1.6822E 06	0.0	0.0
13	1.2706E 07	5.4754E 06	0.0	0.0
14	7.6498E 06	7.2343E 06	4.2229E 06	1.8966E 06
15	1.5000E 06	1.9055E 06	1.3918E 06	7.5809E 05
16	2.6177E 05	4.3386E 05	7.7667E 05	7.5812E 05
17	1.6749E 06	1.7363E 06	1.5078E 06	9.6148E 05
18	9.2995E 05	6.3593E 05	3.1502E 05	1.3556E 05
19	2.3009E 04	2.5776E 04	2.6157E 04	2.1261E 04
20	8.0755E 02	6.3117E 02	4.1807E 02	3.2631E 02
21	4.3476E 01	3.8121E 01	2.9814E 01	2.3962E 01
22	2.7418E 00	2.8753E 00	2.7897E 00	2.3716E 00
23	2.7804E-02	2.7234E-02	2.3267E-02	3.0201E-02
24	1.0518E-04	1.0430E-04	4.7278E-05	6.5036E-05
25	6.0773E-07	6.1262E-07	1.1099E-06	1.0248E-06

^aAngular flux on detector side of Pb slab.

Table C12. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 70° on 5-cm-Thick Pb Slab^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	4.6841E 05	0.0	0.0	0.0
12	1.6848E 06	2.2564E 05	0.0	0.0
13	2.2860E 06	8.5681E 05	0.0	0.0
14	4.4719E 06	4.4575E 06	2.8455E 06	1.0566E 06
15	9.7423E 05	1.2549E 06	9.7776E 05	4.5879E 05
16	2.5959E 05	4.3138E 05	7.7652E 05	7.5812E 05
17	1.6749E 06	1.7363E 06	1.5078E 06	9.6148E 05
18	9.2995E 05	6.3593E 05	3.1502E 05	1.3556E 05
19	2.3009E 04	2.5776E 04	2.6157E 04	2.1261E 04
20	6.9406E 02	4.9406E 02	2.9283E 02	2.2521E 02
21	4.0149E 01	3.4297E 01	2.6153E 01	2.2005E 01
22	2.5412E 00	2.7361E 00	2.7508E 00	2.5074E 00
23	2.5469E-02	2.4651E-02	2.1408E-02	1.0416E-02
24	9.1210E-05	8.5841E-05	5.9643E-05	1.1249E-04
25	5.4922E-07	5.5059E-07	2.0006E-07	8.5375E-07

^aAngular flux on detector side of Pb slab.

Table C13. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 0.808° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	4.7639E-02	4.7980E-02	4.8574E-02	4.6776E-02
3	9.4381E-02	9.4646E-02	9.2040E-02	7.9356E-02
4	7.7682E-01	8.0716E-01	8.9527E-01	8.3065E-01
5	1.6594E-02	1.6992E-02	1.8158E-02	1.7270E-02
6	1.5906E-02	1.6339E-02	1.7655E-02	1.6816E-02
7	1.3058E-03	1.3251E-03	1.3791E-03	1.3220E-03
8	3.1195E-02	3.2519E-02	3.6706E-02	3.5029E-02
9	3.2541E-02	8.4107E-02	8.7946E-02	8.2795E-02
10	4.2308E-02	4.3380E-02	4.5758E-02	4.1920E-02
11	4.4612E-02	4.4980E-02	4.4568E-02	3.9902E-02
12	1.4633E-03	1.4570E-03	1.3958E-03	1.2850E-03
13	9.1744E-02	9.0771E-02	8.4770E-02	7.6356E-02
14	1.0162E-03	9.9957E-02	9.1170E-02	8.0760E-02
15	2.5198E-02	2.4544E-02	2.1336E-02	1.7936E-02
16	1.0697E-02	1.0614E-02	1.0041E-02	9.1968E-01
17	3.0725E-01	3.1897E-01	3.6647E-01	3.9676E-01
18	5.9539E-00	7.2319E-00	8.9300E-00	1.1084E-01
19	1.3531E-00	1.3568E-00	1.4032E-00	1.4851E-00
20	2.6068E-01	2.5944E-01	2.5475E-01	2.5099E-01
21	3.9568E-02	3.9467E-02	3.8862E-02	3.7973E-02
22	3.3989E-02	3.3970E-02	3.3843E-02	3.3613E-02
23	1.3156E-02	1.3153E-02	1.3132E-02	1.3077E-02
24	4.0874E-03	4.0869E-03	4.0766E-03	3.878E-03
25	1.6430E-03	1.6383E-03	1.5702E-03	1.2152E-03

^aAngular flux on detector side of slab.

^bENDF/B-IV Pb MAT 1288 data used in DOT4PI-M calculation.

Table C14. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 30° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	5.5115E-02	5.5487E-02	5.5996E-02	5.3546E-02
3	9.6164E-02	9.6234E-02	9.2868E-02	7.8974E-02
4	8.6637E-01	8.9748E-01	9.8327E-01	9.0371E-01
5	1.9112E-02	1.9534E-02	2.0699E-02	1.9501E-02
6	1.8271E-02	1.8738E-02	2.0096E-02	1.8965E-02
7	1.5166E-03	1.5379E-03	1.5918E-03	1.5084E-03
8	3.6252E-02	3.7767E-02	4.2436E-02	4.0117E-02
9	9.5268E-02	9.7012E-02	1.0092E-03	9.3998E-02
10	4.9055E-02	5.0265E-02	5.2756E-02	4.7867E-02
11	5.1586E-02	5.1971E-02	5.1210E-02	4.5419E-02
12	1.6662E-03	1.6573E-03	1.5775E-03	1.4397E-03
13	1.0444E-03	1.0321E-03	9.6759E-02	8.5595E-02
14	1.1259E-03	1.1065E-03	1.0054E-03	8.8748E-02
15	2.8283E-02	2.7538E-02	2.3899E-02	2.0069E-02
16	1.1928E-02	1.1844E-02	1.1233E-02	1.0305E-02
17	3.4131E-01	3.5463E-01	4.0880E-01	4.4384E-01
18	7.7361E-00	8.0393E-00	9.9103E-00	1.2306E-01
19	1.5124E-00	1.5165E-00	1.5681E-00	1.6588E-00
20	2.9289E-01	2.9149E-01	2.8610E-01	2.8174E-01
21	4.4470E-02	4.4355E-02	4.3668E-02	4.2665E-02
22	3.8242E-02	3.8219E-02	3.8064E-02	3.7793E-02
23	1.4804E-02	1.4800E-02	1.4774E-02	1.4709E-02
24	4.6323E-03	4.6316E-03	4.6197E-03	4.4078E-03
25	1.8621E-03	1.8568E-03	1.7804E-03	1.3829E-03

^aAngular flux on detector side of slab.

^bENDF/B-IV Pb MAT 1283 data used in DOT 4PI-M calculation.

Table C15. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 50° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.6525E-02	6.6783E-02	6.6104E-02	6.1210E-02
3	9.6210E-02	9.6066E-02	9.0748E-02	7.4707E-02
4	9.9370E-01	1.0232E-02	1.0879E-02	9.6515E-01
5	2.2650E-02	2.3046E-02	2.3792E-02	2.1564E-02
6	2.1669E-02	2.2133E-02	2.3158E-02	2.1031E-02
7	1.8070E-03	1.8265E-03	1.8478E-03	1.6799E-03
8	4.4153E-02	4.5835E-02	5.0288E-02	4.5650E-02
9	1.1346E-03	1.1517E-03	1.1713E-03	1.0500E-03
10	5.9354E-02	6.0578E-02	6.2012E-02	5.4208E-02
11	6.1695E-02	6.1896E-02	5.5482E-02	5.1018E-02
12	1.9251E-03	1.9075E-03	1.7770E-03	1.5816E-03
13	1.2009E-03	1.1821E-03	1.0748E-03	9.4048E-02
14	1.2426E-03	1.2184E-03	1.0948E-03	9.5661E-02
15	3.1557E-02	3.0705E-02	2.6564E-02	2.2243E-02
16	1.3021E-02	1.2949E-02	1.2354E-02	1.1378E-02
17	3.6859E-01	3.8355E-01	4.4512E-01	4.8645E-01
18	8.3337E-00	8.6554E-00	1.0673E-01	1.3296E-01
19	1.6296E-00	1.6340E-00	1.6900E-00	1.7887E-00
20	3.1427E-01	3.1262E-01	3.0618E-01	3.0090E-01
21	4.7439E-02	4.7307E-02	4.6529E-02	4.5406E-02
22	4.0721E-02	4.0689E-02	4.0492E-02	4.0171E-02
23	1.5754E-02	1.5748E-02	1.5715E-02	1.5632E-02
24	4.9834E-03	4.9824E-03	4.9664E-03	4.6808E-03
25	1.9992E-03	1.9920E-03	1.8888E-03	1.3514E-03

^aAngular flux on detector side of slab.

^bENDF/B-IV Pb MAT 1288 data used in DOT4PI-M calculation.

Table C16. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 70° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	7.2304E-02	7.1760E-02	6.5744E-02	5.3911E-02
3	8.4289E-02	8.3542E-02	7.5153E-02	5.7790E-02
4	1.0276E-02	1.0443E-02	1.0263E-02	8.1053E-01
5	2.3657E-02	2.3786E-02	2.2684E-02	1.8037E-02
6	2.2943E-02	2.3168E-02	2.2443E-02	1.7897E-02
7	1.8725E-03	1.8723E-03	1.7543E-03	1.3967E-03
8	4.9751E-02	5.1006E-02	5.1494E-02	4.0823E-02
9	1.1994E-03	1.2037E-03	1.1339E-03	9.0239E-02
10	6.5649E-02	6.6071E-02	6.2109E-02	4.8283E-02
11	6.5771E-02	6.5049E-02	5.7557E-02	4.4663E-02
12	1.8797E-03	1.8402E-03	1.6072E-03	1.3414E-03
13	1.1493E-03	1.1186E-03	9.6159E-02	7.9945E-02
14	1.1196E-03	1.0913E-03	9.5476E-02	8.1576E-02
15	2.8134E-02	2.7368E-02	2.3634E-02	1.9733E-02
16	1.0968E-02	1.0951E-02	1.0618E-02	9.9005E-01
17	3.0420E-01	3.1714E-01	3.7245E-01	4.1333E-01
18	6.7872E-00	7.0569E-00	8.7680E-00	1.1032E-01
19	1.3077E-00	1.3113E-00	1.3590E-00	1.4435E-00
20	2.4253E-01	2.4090E-01	2.3428E-01	2.2867E-01
21	3.5303E-02	3.5183E-02	3.4488E-02	3.3507E-02
22	2.9750E-02	2.9718E-02	2.9528E-02	2.9244E-02
23	1.1470E-02	1.1464E-02	1.1432E-02	1.1324E-02
24	3.6611E-03	3.6598E-03	3.6332E-03	3.0787E-03
25	1.4458E-03	1.4317E-03	1.2286E-03	1.6970E-04

^aAngular flux on detector side of slab.

^bENDF/B-IV Pb MAT 1288 data used in DOT4PI-M calculation.

Table C17. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 0.808° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	4.9617E-02	4.9974E-02	5.0605E-02	4.8744E-02
3	5.1180E-02	5.1328E-02	4.9943E-02	4.3110E-02
4	6.3743E-01	6.5609E-01	7.0943E-01	6.6615E-01
5	1.5758E-02	1.6057E-02	1.6919E-02	1.6185E-02
6	1.5077E-02	1.5424E-02	1.6476E-02	1.5783E-02
7	1.3240E-03	1.3429E-03	1.3949E-03	1.3372E-03
8	3.0818E-02	3.2104E-02	3.6185E-02	3.4527E-02
9	8.3046E-02	8.4596E-02	8.8390E-02	8.3302E-02
10	4.2056E-02	4.3132E-02	4.5554E-02	4.1338E-02
11	4.4390E-02	4.4779E-02	4.4467E-02	3.9920E-02
12	1.4777E-03	1.4716E-03	1.4110E-03	1.3002E-03
13	9.2605E-02	9.1653E-02	8.5705E-02	7.7279E-02
14	8.9935E-02	8.8465E-02	8.0757E-02	7.1550E-02
15	2.4113E-02	2.3479E-02	2.0403E-02	1.7194E-02
16	1.0302E-02	1.0230E-02	9.7089E-03	8.9210E-03
17	2.9462E-01	3.0664E-01	3.5523E-01	3.8630E-01
18	6.7639E-00	7.0115E-00	8.5781E-00	1.0625E-01
19	1.3435E-00	1.3475E-00	1.3927E-00	1.4699E-00
20	2.6221E-01	2.6103E-01	2.5652E-01	2.5294E-01
21	4.1071E-02	4.0975E-02	4.0396E-02	3.9536E-02
22	3.5869E-02	3.5849E-02	3.5719E-02	3.5483E-02
23	1.3919E-02	1.3916E-02	1.3894E-02	1.3836E-02
24	4.3819E-03	4.3813E-03	4.3703E-03	4.1674E-03
25	1.7616E-03	1.7566E-03	1.6833E-03	1.3018E-03

^a Angular flux on detector side of Pb slab.

^b DNA MAT 4136, Mod 4 data used in DOT4PI-M calculation.

Table C18. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 30° on 5-cm-Thick Pb Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	5.7381E-02	5.7771E-02	5.8314E-02	5.5778E-02
3	5.2244E-02	5.2334E-02	5.0521E-02	4.3054E-02
4	7.2300E-01	7.4240E-01	7.9487E-01	7.4030E-01
5	1.8275E-02	1.8598E-02	1.9467E-02	1.8445E-02
6	1.7446E-02	1.7828E-02	1.8931E-02	1.7967E-02
7	1.5366E-03	1.5574E-03	1.6091E-03	1.5247E-03
8	3.5928E-02	3.7406E-02	4.1980E-02	3.9783E-02
9	9.5884E-02	9.7613E-02	1.0147E-03	9.4596E-02
10	4.8885E-02	5.0080E-02	5.2620E-02	4.7346E-02
11	5.1426E-02	5.1832E-02	5.1172E-02	4.5489E-02
12	1.6823E-03	1.6735E-03	1.5942E-03	1.4561E-03
13	1.0542E-03	1.0421E-03	9.6794E-02	8.6597E-02
14	1.0093E-03	9.9194E-02	9.0181E-02	7.9695E-02
15	2.7218E-02	2.6494E-02	2.2985E-02	1.9344E-02
16	1.1542E-02	1.1469E-02	1.0910E-02	1.0038E-02
17	3.2892E-01	3.4254E-01	3.9786E-01	4.3372E-01
18	7.5517E-00	7.8248E-00	9.5658E-00	1.1856E-01
19	1.5041E-00	1.5085E-00	1.5589E-00	1.6449E-00
20	2.9471E-01	2.9335E-01	2.8813E-01	2.8395E-01
21	4.6144E-02	4.6034E-02	4.5372E-02	4.4395E-02
22	4.0324E-02	4.0300E-02	4.0140E-02	3.9862E-02
23	1.5649E-02	1.5644E-02	1.5617E-02	1.5549E-02
24	4.9596E-03	4.9588E-03	4.9461E-03	4.7185E-03
25	1.9939E-03	1.9882E-03	1.9061E-03	1.4787E-03

^a Angular flux on detector side of Pb slab.

^b DNA MAT 4136, Mod 4 data used in DOT4PI-M calculation.

Table C19. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 50° on 5-cm-Thick Pb Slab^{a, b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	6.9269E-02	6.9542E-02	6.8858E-02	6.3791E-02
3	5.2474E-02	5.2395E-02	4.9483E-02	4.0707E-02
4	8.4651E-01	8.6473E-01	9.0037E-01	8.0858E-01
5	2.1824E-02	2.2124E-02	2.2594E-02	2.0568E-02
6	2.0870E-02	2.1250E-02	2.2041E-02	2.0106E-02
7	1.8294E-03	1.8483E-03	1.8666E-03	1.6961E-03
8	4.3939E-02	4.5588E-02	4.9950E-02	4.5410E-02
9	1.1426E-03	1.1595E-03	1.1782E-03	1.0567E-03
10	5.9289E-02	6.0518E-02	6.1986E-02	5.4253E-02
11	6.1655E-02	6.1874E-02	5.9534E-02	5.1137E-02
12	1.9435E-03	1.9260E-03	1.7950E-03	1.5985E-03
13	1.2123E-03	1.1936E-03	1.0861E-03	9.5095E-02
14	1.1302E-03	1.1080E-03	9.9535E-02	8.6980E-02
15	3.0553E-02	2.9721E-02	2.5704E-02	2.1563E-02
16	1.2656E-02	1.2595E-02	1.2051E-02	1.1128E-02
17	3.5677E-01	3.7203E-01	4.3477E-01	4.7695E-01
18	8.1581E-00	8.4509E-00	1.0344E-01	1.2867E-01
19	1.6219E-00	1.6266E-00	1.6815E-00	1.7757E-00
20	3.1601E-01	3.1440E-01	3.0811E-01	3.0299E-01
21	4.9210E-02	4.9082E-02	4.8326E-02	4.7228E-02
22	4.2929E-02	4.2896E-02	4.2693E-02	4.2362E-02
23	1.6650E-02	1.6643E-02	1.6608E-02	1.6521E-02
24	5.3330E-03	5.3319E-03	5.3147E-03	5.0079E-03
25	2.1396E-03	2.1319E-03	2.0209E-03	1.4434E-03

^a Angular flux on detector side of Pb slab.

^b DNA MAT 4136, Mod 4 data used in DOT4PI-M calculation.

Table C20. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 70° on 5-cm-Thick Pb Slab^{a, b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	7.5440E-02	7.4883E-02	6.8666E-02	5.6335E-02
3	4.6707E-02	4.6307E-02	4.1739E-02	3.2161E-02
4	8.8594E-01	8.9390E-01	8.6098E-01	6.8468E-01
5	2.2862E-02	2.2908E-02	2.1604E-02	1.7175E-02
6	2.2207E-02	2.2362E-02	2.1467E-02	1.7119E-02
7	1.8937E-03	1.8925E-03	1.7689E-03	1.4051E-03
8	4.9692E-02	5.0915E-02	5.1280E-02	4.0593E-02
9	1.2081E-03	1.2121E-03	1.1399E-03	9.0581E-02
10	6.5747E-02	6.6163E-02	6.2136E-02	4.8244E-02
11	6.5865E-02	6.5143E-02	5.7612E-02	4.4670E-02
12	1.8969E-03	1.8570E-03	1.6214E-03	1.3530E-03
13	1.1599E-03	1.1289E-03	9.7042E-02	8.0677E-02
14	1.0285E-03	1.0020E-03	8.7447E-02	7.4554E-02
15	2.7309E-02	2.6560E-02	2.2932E-02	1.9177E-02
16	1.0657E-02	1.0650E-02	1.0362E-02	9.6894E-01
17	2.9403E-01	3.0719E-01	3.6337E-01	4.0497E-01
18	6.6272E-00	6.8735E-00	8.4833E-00	1.0666E-01
19	1.2966E-00	1.3005E-00	1.3473E-00	1.4281E-00
20	2.4252E-01	2.4092E-01	2.3441E-01	2.2891E-01
21	3.6530E-02	3.6413E-02	3.5735E-02	3.4774E-02
22	3.1361E-02	3.1328E-02	3.1131E-02	3.0838E-02
23	1.2125E-02	1.2119E-02	1.2084E-02	1.1970E-02
24	3.9211E-03	3.9198E-03	3.8912E-03	3.2955E-03
25	1.5485E-03	1.5334E-03	1.3152E-03	1.7787E-04

^a Angular flux on detector side of Pb slab.

^b DNA MAT 4136, Mod 4 data used in DOT4PI-M calculation.

Table C21. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 0.808° on 5-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	3.0648E 00	2.5517E 00	0.0	0.0
3	4.5585E 02	3.7947E 02	0.0	0.0
4	6.9337E 04	5.7704E 04	0.0	0.0
5	2.9054E 05	2.4213E 05	0.0	0.0
6	8.5086E 05	7.1003E 05	0.0	0.0
7	2.3439E 06	1.9585E 06	0.0	0.0
8	7.8837E 06	6.5891E 06	0.0	0.0
9	2.3905E 07	2.0023E 07	0.0	0.0
10	8.6490E 07	7.2519E 07	0.0	0.0
11	2.6265E 08	2.2149E 08	0.0	0.0
12	6.0772E 08	5.1884E 08	8.9764E 06	0.0
13	1.1418E 09	9.9055E 08	3.8910E 08	0.0
14	1.5634E 09	1.4005E 09	7.3768E 08	2.6361E 08
15	1.2135E 09	1.1806E 09	1.0113E 09	7.6514E 08
16	1.4930E 08	2.8848E 08	8.3012E 08	1.0395E 09
17	2.2973E 07	2.7734E 08	6.1969E 08	8.8143E 08
18	2.2823E 08	2.0601E 08	1.7810E 08	2.7488E 08
19	1.5887E 08	1.8463E 08	2.7650E 08	3.3076E 08
20	2.0637E 08	2.1222E 08	2.4829E 08	2.6808E 08
21	1.1968E 08	1.2386E 08	1.4674E 08	1.6263E 08
22	6.4014E 07	6.6656E 07	7.9907E 07	8.6750E 07
23	3.0586E 07	3.1579E 07	3.5922E 07	3.5390E 07
24	1.0025E 07	1.0238E 07	1.0816E 07	9.1066E 06
25	1.9277E 06	1.9269E 06	1.7553E 06	1.0916E 06

^a Angular flux on detector side of slab.

Table C22. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 30° on 5-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.9730E 00	0.0	0.0	0.0
3	2.9349E 02	0.0	0.0	0.0
4	4.4639E 04	0.0	0.0	0.0
5	1.8818E 05	0.0	0.0	0.0
6	5.5417E 05	0.0	0.0	0.0
7	1.5349E 06	0.0	0.0	0.0
8	5.1726E 06	0.0	0.0	0.0
9	1.5812E 07	0.0	0.0	0.0
10	5.7449E 07	0.0	0.0	0.0
11	1.7749E 08	0.0	0.0	0.0
12	4.2275E 08	2.1995E 07	0.0	0.0
13	8.2707E 08	3.4033E 08	0.0	0.0
14	1.2207E 09	6.4661E 08	2.8546E 07	0.0
15	1.1420E 09	3.3793E 08	4.2726E 08	0.0
16	4.4510E 08	7.1862E 08	8.2987E 08	5.7953E 08
17	2.2973E 07	2.3161E 08	6.3763E 08	8.8994E 08
18	1.7883E 08	1.3865E 08	3.5212E 08	7.2322E 08
19	2.0731E 08	1.6097E 08	3.4185E 08	4.0894E 08
20	2.2695E 08	1.2173E 08	2.4100E 08	2.5136E 08
21	1.3028E 08	1.3259E 08	1.5577E 08	1.7308E 08
22	7.1167E 07	7.4765E 07	9.0615E 07	9.8662E 07
23	3.3873E 07	3.4871E 07	3.9530E 07	3.8895E 07
24	1.1115E 07	1.1359E 07	1.2010E 07	1.0113E 07
25	2.1371E 06	2.1357E 06	1.9450E 06	1.2137E 06

^a Angular flux on detector side of slab.

Table C23. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 50° on 5-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	4.1250E 08	0.0	0.0	0.0
14	7.6173E 08	1.9524E 08	0.0	0.0
15	1.0219E 09	6.3074E 08	1.4669E 07	0.0
16	8.3677E 08	9.2563E 08	5.3259E 08	1.5055E 08
17	2.2973E 07	2.8161E 08	6.3763E 08	8.8994E 08
18	1.6179E 08	2.4323E 08	7.4658E 08	1.3345E 09
19	2.7913E 08	3.2904E 08	4.3261E 08	5.8398E 08
20	2.6583E 08	2.5250E 08	2.6586E 08	2.7690E 08
21	1.5594E 08	1.5788E 08	1.8517E 08	2.0527E 08
22	8.7190E 07	9.2030E 07	1.1209E 08	1.2206E 08
23	4.1230E 07	4.2382E 07	4.7973E 07	4.7188E 07
24	1.3553E 07	1.3856E 07	1.4655E 07	1.2340E 07
25	2.6053E 06	2.6033E 06	2.3705E 06	1.4791E 06

^a Angular flux on detector side of slab.

Table C24. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 70° on 5-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0
14	3.3320E 08	0.0	0.0	1.5711E 07
15	8.1823E 08	3.3100E 08	0.0	0.0
16	1.1558E 09	8.9839E 08	1.7135E 08	8.5662E 06
17	1.9109E 08	4.8023E 08	7.8952E 08	9.0443E 08
18	3.0471E 08	5.9390E 08	1.5043E 09	2.2186E 09
19	3.8314E 08	4.3875E 08	6.6178E 08	9.3165E 08
20	3.4133E 08	3.1951E 08	3.3584E 08	3.5657E 08
21	2.1523E 08	2.1842E 08	2.5622E 08	2.8214E 08
22	1.2335E 08	1.3045E 08	1.5878E 08	1.7197E 08
23	5.7822E 07	5.9394E 07	6.7176E 07	6.6022E 07
24	1.9073E 07	1.9502E 07	2.0622E 07	1.7350E 07
25	3.6659E 06	3.6628E 06	3.3345E 06	2.0798E 06

^a Angular flux on detector side of slab.

Table C25. Calculated Gamma-Ray Angular Flux for Primary γ -Ray Beam Incident at 0.808° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	4.8758E 00	4.0434E 00	0.0	0.0
3	7.1684E 02	5.9408E 00	0.0	0.0
4	1.0738E 05	8.8918E 04	0.0	0.0
5	4.4401E 05	3.6783E 05	0.0	0.0
6	1.2776E 06	1.0588E 06	0.0	0.0
7	3.4440E 06	2.8549E 06	0.0	0.0
8	1.1262E 07	9.3284E 06	0.0	0.0
9	3.3198E 07	2.7523E 07	0.0	0.0
10	1.1601E 08	9.6179E 07	0.0	0.0
11	3.4087E 08	2.8410E 08	0.0	0.0
12	7.6433E 08	6.4551E 08	1.1138E 08	0.0
13	1.3888E 09	1.1924E 09	4.4324E 08	0.0
14	1.8456E 09	1.6385E 09	8.1835E 08	2.9040E 08
15	1.4250E 09	1.3764E 09	1.1036E 09	7.3660E 08
16	4.2977E 07	5.5074E 07	2.5970E 08	6.1172E 08
17	1.0173E 08	4.0433E 08	7.6901E 08	8.7520E 08
18	3.5977E 08	3.4087E 08	3.2577E 08	3.8291E 08
19	3.2531E 08	3.5045E 08	4.3334E 08	4.3575E 08
20	4.2531E 08	4.2911E 08	4.4293E 08	3.9942E 08
21	3.0874E 08	3.1439E 08	3.3273E 08	3.0923E 08
22	2.1805E 08	2.2187E 08	2.3224E 08	2.0893E 08
23	1.3520E 08	1.3655E 08	1.3627E 08	1.1254E 08
24	5.8225E 07	5.8127E 07	5.3730E 07	3.8219E 07
25	1.3774E 07	1.3446E 07	1.0711E 07	5.7655E 06

^a Angular flux on detector side of H₂O slab

Table C26. Calculated Gamma-Ray Angular Flux for Primary γ -ray Beam Incident at 30° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	3.1118E 00	0.0	0.0	0.0
3	4.5714E 02	0.0	0.0	0.0
4	6.8394E 04	0.0	0.0	0.0
5	2.8427E 05	0.0	0.0	0.0
6	8.2152E 05	0.0	0.0	0.0
7	2.2235E 06	0.0	0.0	0.0
8	7.2716E 06	0.0	0.0	0.0
9	2.1572E 07	0.0	0.0	0.0
10	7.5557E 07	0.0	0.0	0.0
11	2.2586E 08	0.0	0.0	0.0
12	5.2053E 08	2.6977E 07	0.0	0.0
13	9.8466E 08	4.1082E 08	0.0	0.0
14	1.4146E 09	7.6297E 08	7.0816E 07	0.0
15	1.3208E 09	1.0389E 09	4.9203E 08	1.2449E 08
16	1.3517E 08	1.8705E 08	3.4938E 08	6.1630E 08
17	1.0173E 08	4.0659E 08	7.7462E 08	8.7653E 08
18	3.2865E 08	3.2112E 08	5.0541E 08	7.2277E 08
19	3.9077E 08	4.4333E 08	5.1280E 08	5.0759E 08
20	4.5897E 08	4.4771E 08	4.4086E 08	3.8986E 08
21	3.3206E 08	3.3592E 08	3.5477E 08	3.2990E 08
22	2.3831E 08	2.4339E 08	2.5560E 08	2.2970E 08
23	1.4748E 08	1.4877E 08	1.4817E 08	1.2221E 08
24	6.3591E 07	6.3497E 07	5.8689E 07	4.1723E 07
25	1.5047E 07	1.4687E 07	1.1695E 07	6.2931E 06

^a Angular flux on detector side of H₂O slab.

Table C27. Calculated Gamma-Ray Angular Flux for Primary γ -ray Beam Incident at 50° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	9.3166E 07	0.0	0.0	0.0
13	4.7235E 08	0.0	0.0	0.0
14	8.5071E 08	2.4898E 08	0.0	0.0
15	1.1323E 09	7.2195E 08	1.0651E 08	0.0
16	3.2734E 08	3.5904E 08	3.8510E 08	4.7649E 08
17	1.0173E 08	4.0658E 08	7.7461E 08	8.7652E 08
18	3.2406E 08	4.1431E 08	8.2616E 08	1.0906E 09
19	4.7032E 08	5.1920E 08	5.9679E 08	6.1380E 08
20	4.9924E 08	4.7830E 08	4.6307E 08	4.0973E 08
21	3.7098E 08	3.7434E 08	3.9383E 08	3.6388E 08
22	2.6982E 08	2.7610E 08	2.9005E 08	2.5979E 08
23	1.6565E 08	1.6797E 08	1.6705E 08	1.3756E 08
24	7.1996E 07	7.1892E 07	6.6416E 07	4.7171E 07
25	1.7341E 07	1.6631E 07	1.3238E 07	7.1195E 06

^a Angular flux on detector side of H₂O slab.

Table C28. Calculated Gamma-Ray Angular Flux for Primary γ -ray Beam Incident at 70° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	1.8045E 07	0.0	0.0	0.0
14	3.5122E 08	2.4562E 07	0.0	4.9508E 06
15	7.9858E 08	3.5955E 08	0.0	0.0
16	4.0344E 08	3.5677E 08	3.1573E 08	4.4851E 08
17	1.6332E 08	4.8056E 08	8.1635E 08	8.7829E 08
18	4.2991E 08	6.5780E 08	1.1990E 09	1.2789E 09
19	5.4282E 08	5.8432E 08	6.9369E 08	6.8907E 08
20	5.3299E 08	5.0678E 08	4.9172E 08	4.3752E 08
21	4.2253E 08	4.2660E 08	4.4578E 08	4.0610E 08
22	3.1195E 08	3.1921E 08	3.3353E 08	2.9556E 08
23	1.9257E 08	1.9398E 08	1.9237E 08	1.5773E 08
24	8.3533E 07	8.3396E 07	7.6913E 07	5.4476E 07
25	1.9793E 07	1.9314E 07	1.5356E 07	8.2463E 06

^a Angular flux on detector side of H₂O slab.

Table C29. Calculated Gamma-Ray Angular Flux for Primary γ -Ray Beam Incident at 0.808° on 10-cm-Thick H₂O Canned in Al^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	4.8901E 00	4.0877E 00	6.9369E-01	-1.3345E 00
3	7.1947E 02	5.9673E 02	1.0238E 02	-1.9065E 02
4	1.0787E 05	3.9411E 04	1.5395E 04	-2.7518E 04
5	4.4708E 05	3.7104E 05	6.7254E 04	-1.0567E 05
6	1.2893E 06	1.0713E 06	2.0408E 05	-2.7968E 05
7	3.4816E 06	2.8957E 06	5.7907E 05	-6.8404E 05
8	1.1392E 07	9.4734E 06	1.9417E 06	-2.0426E 06
9	3.3617E 07	2.8007E 07	6.1322E 06	-5.1923E 06
10	1.1746E 08	9.7906E 07	2.2287E 07	-1.5759E 07
11	3.4498E 08	2.8889E 08	7.3237E 07	-3.4602E 07
12	7.7076E 08	6.5213E 08	1.9632E 08	-3.7605E 07
13	1.3947E 09	1.1995E 09	4.4518E 08	3.3320E 07
14	1.8441E 09	1.6382E 09	8.1877E 08	2.8951E 08
15	1.4164E 09	1.3676E 09	1.1053E 09	7.3696E 08
16	2.7829E 08	4.2621E 08	9.3330E 08	1.0085E 09
17	2.4995E 08	2.7029E 08	4.4156E 08	6.8691E 08
18	3.6268E 08	3.4795E 08	3.3421E 08	3.5313E 08
19	3.1192E 08	3.3537E 08	4.2077E 08	4.2992E 08
20	4.1249E 08	4.1885E 08	4.3578E 08	3.5399E 08
21	3.0775E 08	3.1309E 08	3.3015E 08	3.0610E 08
22	2.1523E 08	2.1913E 08	2.2973E 08	2.0699E 08
23	1.3354E 08	1.3487E 08	1.3459E 08	1.1120E 08
24	5.7497E 07	5.7402E 07	5.3068E 07	3.7755E 07
25	1.3601E 07	1.3277E 07	1.0577E 07	5.6938E 06

^a Angular flux on detector side of H₂O slab.

^b Negative fluxes not suppressed.

Table C30. Calculated Gamma-Ray Angular Flux for Primary γ -ray Beam Incident at 30° on 10-cm-Thick H₂O Canned in Al^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	3.1186E 00	5.4826E-01	-1.2332E 00	-5.1752E-02
3	4.5840E 02	8.1345E 01	-1.7966E 02	-7.6674E 00
4	6.8629E 04	1.2315E 04	-2.6457E 04	-1.1573E 03
5	2.8584E 05	5.4544E 04	-1.0531E 05	-5.8194E 03
6	8.2774E 05	1.6765E 05	-2.9021E 05	-1.9591E 04
7	2.2435E 06	4.8224E 05	-7.4448E 05	-6.0842E 04
8	7.3412E 06	1.6369E 06	-2.3296E 06	-2.1274E 05
9	2.1793E 07	5.2521E 06	-6.3788E 06	-7.3184E 05
10	7.6282E 07	1.9357E 07	-2.0839E 07	-2.7289E 06
11	2.2711E 08	6.4770E 07	-5.3500E 07	-9.4247E 06
12	5.2204E 08	1.7700E 08	-9.1702E 07	-2.4799E 07
13	9.8633E 08	4.0840E 08	-9.1138E 07	-4.5341E 07
14	1.4149E 09	7.8251E 08	7.2809E 07	-2.9876E 07
15	1.3187E 09	1.0395E 09	4.9211E 08	1.4117E 08
16	5.9879E 08	8.7462E 08	9.0846E 08	5.8041E 08
17	3.1457E 08	4.0522E 08	8.0620E 08	1.0131E 09
18	3.4902E 08	3.4936E 08	5.4133E 08	7.7658E 08
19	3.7861E 08	4.2995E 08	5.0809E 08	5.1171E 08
20	4.4841E 08	4.4150E 08	4.3864E 08	3.9068E 08
21	3.3906E 08	3.4216E 08	3.6904E 08	3.3301E 08
22	2.3958E 08	2.4502E 08	2.5805E 08	2.3245E 08
23	1.4824E 08	1.4952E 08	1.4897E 08	1.2297E 08
24	6.3895E 07	6.3806E 07	5.8995E 07	4.1961E 07
25	1.5115E 07	1.4753E 07	1.1750E 07	6.3244E 06

^a Angular flux on detector side of H₂O slab.

^b Negative fluxes not suppressed.

Table C31. Calculated Gamma-Ray Angular Flux for Primary γ -Ray Beam Incident at 50° on 10-cm-Thick H₂O Canned in Al^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	8.2079E-01	-1.1527E 00	-3.9571E-02	1.9600E 00
3	1.2094E 02	-1.6719E 02	-5.7766E 00	2.7850E 02
4	1.8147E 04	-2.4612E 04	-8.6244E 02	3.9885E 04
5	7.8748E 04	-9.7133E 04	-4.1847E 03	1.5422E 05
6	2.3695E 05	-2.6470E 05	-1.3726E 04	4.1036E 05
7	6.6658E 05	-8.6921E 05	-4.2393E 04	1.0086E 06
8	2.2199E 06	-2.0708E 06	-1.5002E 05	2.9923E 06
9	6.9296E 06	-5.5082E 06	-5.2806E 05	7.7339E 06
10	2.4949E 07	-1.7541E 07	-2.0264E 06	2.3623E 07
11	8.0681E 07	-4.1599E 07	-7.3002E 06	5.6588E 07
12	2.1200E 08	-5.5775E 07	-2.0144E 07	9.1591E 07
13	4.7171E 08	-1.3460E 06	-3.8704E 07	9.6835E 07
14	8.5219E 08	2.5025E 08	-2.6561E 07	2.0420E 07
15	1.1358E 09	7.2676E 08	1.3640E 08	-6.2421E 07
16	9.6629E 08	1.0331E 09	5.9534E 08	2.3145E 08
17	4.9745E 08	6.9728E 08	1.1083E 09	1.0548E 09
18	3.7699E 08	4.7376E 08	8.9923E 08	1.1913E 09
19	4.7560E 08	5.2393E 08	6.1254E 08	6.3545E 08
20	5.0822E 08	4.9116E 08	4.7933E 08	4.2898E 08
21	3.9488E 08	3.9770E 08	4.1641E 08	3.8430E 08
22	2.8326E 08	2.9019E 08	3.0546E 08	2.7402E 08
23	1.7474E 08	1.7612E 08	1.7523E 08	1.4443E 08
24	7.5473E 07	7.5369E 07	6.9651E 07	4.9491E 07
25	1.7858E 07	1.7429E 07	1.3876E 07	7.4645E 06

^a Angular flux on detector side of H₂O slab.

^b Negative fluxes not suppressed.

Table C32. Calculated Gamma-Ray Angular Flux for Primary γ -ray Beam Incident at 70° on 10-cm-Thick H₂O Canned in Al^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	-9.7328E-01	-1.1128E 00	1.9602E 00	1.2266E 00
3	-1.3884E 02	-1.5955E 02	2.7856E 02	1.7147E 02
4	-1.9996E 04	-2.3122E 04	3.9894E 04	2.4029E 04
5	-7.6757E 04	-9.2484E 04	1.5547E 05	9.2600E 04
6	-2.0137E 05	-2.5432E 05	4.1513E 05	2.4477E 05
7	-4.8511E 05	-6.4827E 05	1.0216E 06	5.9783E 05
8	-1.4238E 06	-1.9845E 06	3.0224E 06	1.7404E 06
9	-3.5005E 06	-5.4138E 06	7.8110E 06	4.5179E 06
10	-1.0211E 07	-1.7321E 07	2.3756E 07	1.3609E 07
11	-1.9828E 07	-4.5206E 07	5.6784E 07	3.3653E 07
12	-7.9737E 06	-8.2983E 07	9.1198E 07	5.9370E 07
13	8.2266E 07	-9.9737E 07	9.3997E 07	7.2007E 07
14	3.5241E 08	6.5246E 06	1.4396E 07	3.0427E 07
15	8.0412E 08	3.6244E 08	-6.2675E 07	-5.4735E 07
16	1.0991E 09	8.7343E 08	2.6617E 08	6.6357E 07
17	8.2516E 08	1.0533E 09	1.1524E 09	7.8665E 08
18	4.9219E 08	7.2355E 08	1.2859E 09	1.3940E 09
19	5.5662E 08	6.0091E 08	7.1801E 08	7.1500E 08
20	5.5105E 08	5.2750E 08	5.1528E 08	4.6309E 08
21	4.5330E 08	4.5662E 08	4.7468E 08	4.3100E 08
22	3.3157E 08	3.3954E 08	3.5499E 08	3.1453E 08
23	2.0447E 08	2.0596E 08	2.0427E 08	1.6753E 08
24	8.8714E 07	8.8570E 07	8.1690E 07	5.7865E 07
25	2.1018E 07	2.0509E 07	1.6307E 07	8.7576E 06

^a Angular flux on detector side of H₂O slab.

^b Negative fluxes not suppressed.

Table C33. Calculation Gamma-Ray Angular Flux for Neutron Beam Incident at 0.808° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	2.4086E-02	2.5449E-02	3.4865E-02	5.427CE-02
2	5.7003E-01	6.0238E-01	8.2365E-01	1.2673E 00
3	2.5437E 02	2.6768E 02	3.5344E 02	4.935CE 02
4	1.7621E 02	1.8267E 02	2.2520E 02	2.945EE 02
5	2.8219E 02	3.0064E 02	4.0654E 02	5.438CE 02
6	1.7742E 02	1.9313E 02	2.7600E 02	3.6832E 02
7	1.9800E 02	2.1513E 02	3.0366E 02	3.9775E 02
8	3.6067E 04	3.8001E 04	4.9604E 04	6.3957E 04
9	1.6605E 03	2.2838E 03	5.4369E 03	8.5958E 03
10	1.4791E 03	1.8880E 03	3.9679E 03	6.0092E 03
11	2.1390E 03	2.3935E 03	3.7340E 03	5.0627E 03
12	2.5125E 03	2.6309E 03	3.3206E 03	4.0457E 03
13	2.9081E 03	2.9227E 03	3.1151E 03	3.388CE 03
14	3.6805E 03	3.6672E 03	3.7115E 03	3.803CE 03
15	3.4178E 03	3.4302E 03	3.5269E 03	3.533CE 03
16	3.0826E 03	3.2104E 03	3.7865E 03	4.034CE 03
17	2.5102E 03	2.6677E 03	3.4346E 03	3.9062E 03
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^a Angular flux on detector side of H₂O slab.

Table C34. Calculation Gamma-Ray Angular Flux for Neutron Beam Incident at 30° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	2.6578E-02	2.8078E-02	3.8388E-02	5.9330E-02
2	6.2849E-01	6.6407E-01	9.0619E-01	1.3840E 00
3	2.6933E 02	2.8233E 02	3.7275E 02	5.1964E 02
4	1.7636E 02	1.7289E 02	2.1719E 02	3.0705E 02
5	2.9958E 02	3.1898E 02	4.3111E 02	5.7184E 02
6	1.8868E 02	2.0538E 02	2.9379E 02	3.8893E 02
7	2.1158E 02	2.2987E 02	3.2396E 02	4.1818E 02
8	3.4570E 04	3.6424E 04	4.7539E 04	6.1261E 04
9	1.6585E 03	2.2598E 03	5.2941E 03	8.3097E 03
10	1.4319E 03	1.8256E 03	3.8256E 03	5.7806E 03
11	2.0897E 03	2.3348E 03	3.6215E 03	4.8811E 03
12	2.4390E 03	2.5527E 03	3.2130E 03	3.8993E 03
13	2.8116E 03	2.8247E 03	3.0061E 03	3.2648E 03
14	3.5599E 03	3.5468E 03	3.5878E 03	3.6737E 03
15	3.2939E 03	3.3062E 03	3.4003E 03	3.4060E 03
16	2.9656E 03	3.0897E 03	3.6474E 03	3.8858E 03
17	2.4163E 03	2.5679E 03	3.3065E 03	3.7606E 03
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^a Angular flux on detector side of H₂O slab.

Table C35. Calculation Gamma-Ray Angular Flux for Neutron Beam Incident at 50° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	3.2238E-02	3.4039E-02	4.6213E-02	6.9651E-02
2	7.5523E-01	7.9767E-01	1.0814E 00	1.6117E 00
3	3.1805E 02	3.3372E 02	4.4150E 02	6.0860E 02
4	1.8859E 02	1.8719E 02	2.5753E 02	3.8182E 02
5	3.5528E 02	3.7863E 02	5.1103E 02	6.6397E 02
6	2.2258E 02	2.4289E 02	3.4820E 02	4.5151E 02
7	2.5129E 02	2.7347E 02	3.8409E 02	4.7783E 02
8	3.2795E 04	3.4554E 04	4.5048E 04	5.7816E 04
9	1.7433E 03	2.3265E 03	5.2451E 03	8.0574E 03
10	1.4031E 03	1.7828E 03	3.6988E 03	5.5414E 03
11	2.0858E 03	2.3207E 03	3.5419E 03	4.6890E 03
12	2.3995E 03	2.5064E 03	3.1246E 03	3.7453E 03
13	2.7383E 03	2.7470E 03	2.9054E 03	3.1390E 03
14	3.4584E 03	3.4432E 03	3.4728E 03	3.5450E 03
15	3.1690E 03	3.1814E 03	3.2735E 03	3.2764E 03
16	2.8329E 03	2.9555E 03	3.5019E 03	3.7302E 03
17	2.3129E 03	2.4579E 03	3.1659E 03	3.6007E 03
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^a Angular flux on detector side of H₂O slab.

Table C36. Calculation Gamma-Ray Angular Flux for Neutron Beam Incident at 70° on 10-cm-Thick H₂O Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	4.9673E-02	5.2384E-02	6.9976E-02	9.9158E-02
2	1.1050E 00	1.1658E 00	1.5553E 00	2.1777E 00
3	4.4699E 02	4.7048E 02	6.2186E 02	8.3707E 02
4	2.3600E 02	2.4806E 02	3.6890E 02	5.3436E 02
5	5.0726E 02	5.4137E 02	7.2755E 02	9.1325E 02
6	3.0992E 02	3.3973E 02	4.8777E 02	6.0912E 02
7	3.7250E 02	4.0582E 02	5.6343E 02	6.5752E 02
8	3.0233E 04	3.1854E 04	4.1420E 04	5.2618E 04
9	2.0320E 03	2.6008E 03	5.3931E 03	7.8717E 03
10	1.4006E 03	1.7664E 03	3.5834E 03	5.2588E 03
11	2.2162E 03	2.4409E 03	3.5776E 03	4.5183E 03
12	2.4473E 03	2.5456E 03	3.1034E 03	3.6010E 03
13	2.7101E 03	2.7098E 03	2.8252E 03	3.0119E 03
14	3.3882E 03	3.3666E 03	3.3672E 03	3.4075E 03
15	3.0425E 03	3.0552E 03	3.1447E 03	3.1389E 03
16	2.6706E 03	2.7956E 03	3.3415E 03	3.5564E 03
17	2.1897E 03	2.3273E 03	3.0011E 03	3.4122E 03
18	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0

^a Angular flux on detector side of H₂O slab.

Table C37. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 0.808° on 10.6-cm-Thick H₂O Slab^{a, b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.2530E-01	1.3259E-01	1.8360E-01	2.9161E-01
3	1.6075E 01	1.6323E 01	1.9017E 01	2.6413E 01
4	7.4501E 01	7.2507E 01	6.7591E 01	7.4275E 01
5	1.3090E 00	1.5574E 00	3.0078E 00	5.1708E 00
6	2.0495E 01	2.1794E 01	3.0158E 01	4.4361E 01
7	2.7145E 00	3.1896E 00	5.8785E 00	9.5664E 00
8	3.8606E 04	4.0705E 04	5.3491E 04	7.0650E 04
9	1.0215E 03	1.6319E 03	4.7179E 03	7.9436E 03
10	1.4137E 03	1.8156E 03	3.8847E 03	6.0334E 03
11	1.0588E 03	2.0982E 03	3.3868E 03	4.7581E 03
12	2.3362E 03	2.4451E 03	3.1111E 03	3.8931E 03
13	2.7938E 03	2.8069E 03	3.0095E 03	3.3538E 03
14	3.4903E 03	3.4785E 03	3.5400E 03	3.6898E 03
15	3.2709E 03	3.2870E 03	3.4115E 03	3.4861E 03
16	2.9335E 03	3.0630E 03	3.6674E 03	3.9993E 03
17	2.3403E 03	2.4991E 03	3.2999E 03	3.8707E 03
18	2.2509E 03	2.3330E 03	2.7206E 03	2.8834E 03
19	2.2299E 03	2.2894E 03	2.5577E 03	2.6000E 03
20	1.8173E 03	1.8725E 03	2.1090E 03	2.1282E 03
21	1.4620E 03	1.4999E 03	1.6542E 03	1.6343E 03
22	1.0663E 03	1.0910E 03	1.1847E 03	1.1467E 03
23	6.6662E 02	6.7999E 02	7.2222E 02	6.8188E 02
24	3.1667E 02	3.2106E 02	3.3127E 02	3.0306E 02
25	9.4723E 01	9.5251E 01	9.4099E 01	8.2792E 01

^a Angular flux on detector side of 10.6 slab.

^b No Al can.

Table C38. Calculated Gamma-Ray Angular Flux for Neutron Beam Incident at 30° on 10.6-cm-Thick H₂O Slab^{a, b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.3875E-01	1.4681E-01	2.0310E-01	3.2160E-01
3	1.6124E 01	1.5198E 01	1.8817E 01	2.8121E 01
4	6.7381E 01	5.4116E 01	4.7738E 01	7.4047E 01
5	1.0462E 00	1.0613E 00	2.8571E 00	5.8950E 00
6	2.1994E 01	2.3212E 01	3.2428E 01	4.8118E 01
7	2.7623E 00	3.1380E 00	6.1970E 00	1.0534E 01
8	3.7031E 04	3.9044E 04	5.1301E 04	6.7735E 04
9	9.8210E 02	1.5680E 03	4.5283E 03	7.6185E 03
10	1.3586E 03	1.7442E 03	3.7280E 03	5.7863E 03
11	1.7857E 03	2.0151E 03	3.2497E 03	4.5631E 03
12	2.2435E 03	2.3476E 03	2.9847E 03	3.7335E 03
13	2.6817E 03	2.6939E 03	2.8870E 03	3.2165E 03
14	3.3547E 03	3.3435E 03	3.4031E 03	3.5465E 03
15	3.1378E 03	3.1535E 03	3.2739E 03	3.3458E 03
16	2.8130E 03	2.9379E 03	3.5184E 03	3.8372E 03
17	2.2451E 03	2.3973E 03	3.1652E 03	3.7130E 03
18	2.1597E 03	2.2386E 03	2.6105E 03	2.7668E 03
19	2.1396E 03	2.1967E 03	2.4541E 03	2.4951E 03
20	1.7438E 03	1.7968E 03	2.0237E 03	2.0420E 03
21	1.4029E 03	1.4392E 03	1.5872E 03	1.5681E 03
22	1.0231E 03	1.0469E 03	1.1368E 03	1.1002E 03
23	6.3965E 02	6.5200E 02	6.9300E 02	6.5428E 02
24	3.0386E 02	3.0807E 02	3.1787E 02	2.9080E 02
25	9.0891E 01	9.1397E 01	9.0292E 01	7.9442E 01

^a Angular flux on detector side of 10.6 slab.

^b No Al can.

Table C39. Calculated Gamma-Ray Angular Flux for Neutron Beam
Incident at 50° on 10.6-cm-Thick H₂O Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.6268E-01	1.7210E-01	2.3750E-01	3.7209E-01
3	1.6500E 01	1.5665E 01	2.0919E 01	3.5192E 01
4	5.7543E 01	4.4461E 01	5.5896E 01	1.1160E 02
5	6.2256E-01	8.0061E-01	3.8990E 00	8.5350E 00
6	2.4586E 01	2.6084E 01	3.7192E 01	5.5032E 01
7	2.8777E 00	3.4114E 00	7.5228E 00	1.2994E 01
8	3.3698E 04	3.5529E 04	4.6672E 04	6.1575E 04
9	8.9760E 02	1.4317E 03	4.1272E 03	6.9336E 03
10	1.2411E 03	1.5921E 03	3.3967E 03	5.2655E 03
11	1.6302E 03	1.8386E 03	2.9599E 03	4.1520E 03
12	2.0467E 03	2.1407E 03	2.7177E 03	3.3970E 03
13	2.4443E 03	2.4548E 03	2.6280E 03	2.9267E 03
14	3.0660E 03	3.0559E 03	3.1105E 03	3.2386E 03
15	2.0571E 03	2.8718E 03	2.9028E 03	3.0484E 03
16	2.5593E 03	2.6738E 03	3.2037E 03	3.4942E 03
17	2.0442E 03	2.1825E 03	2.8811E 03	3.3798E 03
18	1.9670E 03	2.0390E 03	2.3779E 03	2.5202E 03
19	1.9488E 03	2.0008E 03	2.2351E 03	2.2723E 03
20	1.5887E 03	1.6370E 03	1.8435E 03	1.8600E 03
21	1.2779E 03	1.3110E 03	1.4458E 03	1.4284E 03
22	9.3202E 02	9.5366E 02	1.0355E 03	1.0022E 03
23	5.8270E 02	5.9396E 02	6.3129E 02	5.9602E 02
24	2.7681E 02	2.8064E 02	2.8957E 02	2.6491E 02
25	8.2799E 01	8.3261E 01	8.2254E 01	7.2370E 01

^aAngular flux on detector side of 10.6 slab.

^bNo Al can.

Table C40. Calculated Gamma-Ray Angular Flux for Neutron Beam
Incident at 70° on 10.6-cm-Thick H₂O Slab^{a,b}

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	1.9027E-01	2.0115E-01	2.7504E-01	4.1706E-01
3	1.6929E 01	1.7152E 01	2.5916E 01	4.3201E 01
4	4.6806E 01	4.2849E 01	8.2380E 01	1.6156E 02
5	5.4874E-02	8.1167E-01	6.1665E 00	1.2580E 01
6	2.7024E 01	2.9084E 01	4.2316E 01	6.0148E 01
7	3.0230E 00	3.9752E 00	9.7015E 00	1.6120E 01
8	2.7142E 04	2.8615E 04	3.7558E 04	4.9419E 04
9	7.3093E 02	1.1641E 03	3.3427E 03	5.5938E 03
10	1.0101E 03	1.2938E 03	2.7484E 03	4.2462E 03
11	1.3253E 03	1.4926E 03	2.3925E 03	3.3465E 03
12	1.6611E 03	1.7354E 03	2.1945E 03	2.7368E 03
13	1.9797E 03	1.9866E 03	2.1202E 03	2.3575E 03
14	2.4919E 03	2.4832E 03	2.5236E 03	2.6156E 03
15	2.3063E 03	2.3168E 03	2.4099E 03	2.4614E 03
16	2.0601E 03	2.1534E 03	2.5844E 03	2.8182E 03
17	1.6478E 03	1.7589E 03	2.3209E 03	2.7225E 03
18	1.5869E 03	1.6451E 03	1.9190E 03	2.0330E 03
19	1.5737E 03	1.6156E 03	1.8043E 03	1.8335E 03
20	1.2836E 03	1.3226E 03	1.4890E 03	1.5016E 03
21	1.0322E 03	1.0589E 03	1.1678E 03	1.1535E 03
22	7.5295E 02	7.7042E 02	8.3651E 02	8.0950E 02
23	4.7078E 02	4.7987E 02	5.1001E 02	4.8148E 02
24	2.2365E 02	2.2675E 02	2.3395E 02	2.1402E 02
25	6.6899E 01	6.7272E 01	6.6458E 01	5.8471E 01

^aAngular flux on detector side of 10.6 slab.

^bNo Al can.

Table C41. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray
Beam Incident at 0.808° on 20-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, ϵ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	7.3038E 00	6.0091E 00	0.0	0.0
3	1.0491E 03	8.6178E 02	0.0	0.0
4	1.5243E 05	1.2496E 05	0.0	0.0
5	6.1374E 05	5.0253E 05	0.0	0.0
6	1.7053E 06	1.3941E 06	0.0	0.0
7	4.4029E 06	3.5933E 06	0.0	0.0
8	1.3613E 07	1.1079E 07	0.0	0.0
9	3.7926E 07	3.0831E 07	0.0	0.0
10	1.2364E 08	1.0035E 08	0.0	0.0
11	3.4021E 08	2.7750E 08	0.0	0.0
12	7.1628E 08	5.9277E 08	1.3706E 08	0.0
13	1.2181E 09	1.0266E 09	3.5048E 08	0.0
14	1.5268E 09	1.3340E 09	6.1670E 08	2.1809E 08
15	1.1663E 09	1.1104E 09	8.0972E 08	4.7593E 08
16	5.1020E 07	7.5727E 07	2.2950E 08	4.2328E 08
17	1.5423E 08	3.7478E 08	5.5783E 08	5.3552E 08
18	3.9361E 08	3.8183E 08	3.5988E 08	3.4373E 08
19	4.1793E 08	4.2810E 08	4.3596E 08	3.7771E 08
20	5.5021E 08	5.4209E 08	4.8661E 08	3.8516E 08
21	4.8277E 08	4.7926E 08	4.4088E 08	3.5697E 08
22	4.1383E 08	4.1007E 08	3.7248E 08	2.9308E 08
23	3.0980E 08	3.0506E 08	2.6661E 08	1.9541E 08
24	1.5869E 08	1.5464E 08	1.2645E 08	8.1173E 07
25	4.1272E 07	3.9434E 07	2.8359E 07	1.4173E 07

^a Angular flux on detector side of slab.

Table C42. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray
Beam Incident at 30° on 20-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	4.5818E 00	0.0	0.0	0.0
3	6.5643E 02	0.0	0.0	0.0
4	9.5037E 04	0.0	0.0	0.0
5	3.8404E 05	0.0	0.0	0.0
6	1.0691E 06	0.0	0.0	0.0
7	2.7640E 06	0.0	0.0	0.0
8	8.5156E 06	0.0	0.0	0.0
9	2.3807E 07	0.0	0.0	0.0
10	7.7569E 07	0.0	0.0	0.0
11	2.1706E 08	0.0	0.0	0.0
12	4.6868E 08	1.0019E 08	0.0	0.0
13	8.2994E 08	3.5844E 08	0.0	0.0
14	1.1315E 09	6.3535E 08	1.0001E 08	7.5350E 06
15	1.0479E 09	8.4350E 08	3.9376E 08	1.3267E 08
16	1.9273E 08	2.4999E 08	3.7223E 08	4.0256E 08
17	1.5423E 08	3.7537E 08	5.5860E 08	5.3555E 08
18	3.6733E 08	3.7189E 08	4.4510E 08	4.7220E 08
19	4.5429E 08	4.7902E 08	4.6819E 08	3.9287E 08
20	5.5901E 08	5.3832E 08	4.6731E 08	3.6409E 08
21	4.9270E 08	4.8763E 08	4.4612E 08	3.5887E 08
22	4.2787E 08	4.2438E 08	3.8441E 08	3.0093E 08
23	3.2089E 08	3.1569E 08	2.7499E 08	2.0092E 08
24	1.6481E 08	1.6057E 08	1.3106E 08	8.3976E 07
25	4.2905E 07	4.0984E 07	2.9436E 07	1.4695E 07

^a Angular flux on detector side of slab.

Table C43. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 50° on 20-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	4.5054E 06	0.0	0.0	0.0
12	1.2645E 08	0.0	0.0	0.0
13	3.7471E 08	2.3104E 07	0.0	0.0
14	6.4027E 08	2.3142E 08	8.4348E 06	0.0
15	8.2834E 08	5.5968E 08	1.3561E 08	2.2929E 06
16	2.6186E 08	2.8762E 08	3.1547E 08	2.7081E 08
17	1.5423E 08	3.7537E 08	5.5860E 08	5.3555E 08
18	3.5309E 08	4.1066E 08	5.4174E 08	5.3522E 08
19	4.8322E 08	4.9914E 08	4.7107E 08	3.8690E 08
20	5.4997E 08	5.2363E 08	4.4811E 08	3.4710E 08
21	4.9943E 08	4.9366E 08	4.4779E 08	3.5620E 08
22	4.3925E 08	4.3544E 08	3.9187E 08	3.0427E 08
23	3.3950E 08	3.2484E 08	2.8171E 08	2.0489E 08
24	1.7045E 08	1.6598E 08	1.3508E 08	8.6301E 07
25	4.4435E 07	4.2429E 07	3.0414E 07	1.5158E 07

^aAngular flux on detector side of slab.

Table C44. Calculated Gamma-Ray Angular Flux for Primary Gamma-Ray Beam Incident at 70° on 20-cm-Thick H₂O Slab Canned in Al^a

Gamma-Ray Group	Angular Flux			
	Angle, θ			
	0.808°	20°	50°	70°
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	3.8724E 06	0.0	0.0	0.0
13	5.0986E 07	9.4425E 05	0.0	3.8372E 06
14	2.4310E 08	5.0268E 07	0.0	5.1956E 05
15	4.3817E 08	2.5518E 08	2.6961E 07	0.0
16	2.7539E 08	2.8198E 08	2.9483E 08	2.5423E 08
17	1.7115E 08	3.9413E 08	5.6423E 08	5.3559E 08
18	3.7031E 08	4.5313E 08	5.3075E 08	4.2307E 08
19	4.6255E 08	4.6081E 08	4.1100E 08	3.1539E 08
20	4.9168E 08	4.6661E 08	3.9653E 08	3.0472E 08
21	4.7163E 08	4.6622E 08	4.1710E 08	3.2613E 08
22	4.2119E 08	4.1644E 08	3.6959E 08	2.8286E 08
23	3.1921E 08	3.1330E 08	2.6956E 08	1.9448E 08
24	1.6582E 08	1.6130E 08	1.3054E 08	8.2961E 07
25	4.3343E 07	4.1357E 07	2.9537E 07	1.4676E 07

^aAngular flux on detector side of slab.

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