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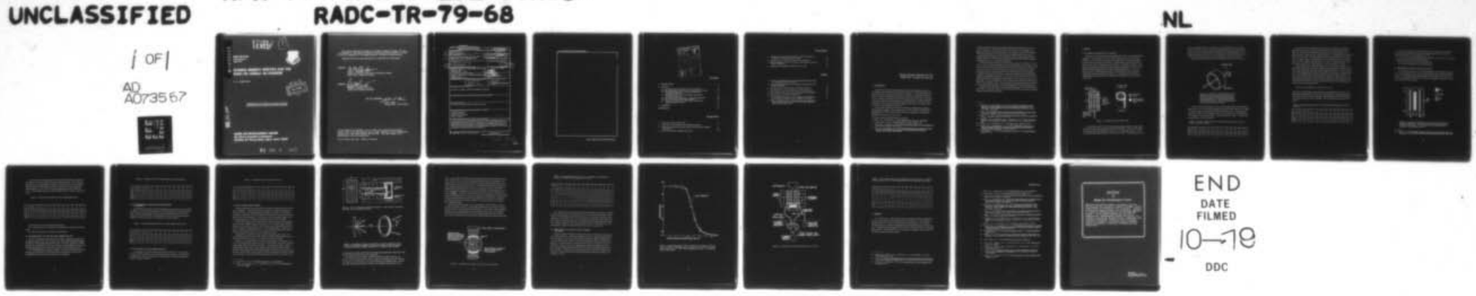

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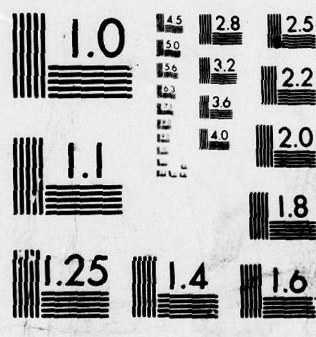

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In-House Report
April 1979

GAMMA ENERGY SPECTRA FOR THE RADC/ES COBALT 60 SOURCES

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A monte carlo photon transport code has been used to calculate the photon energy distributions produced by several in-use intense ^{60}Co sources at RADC/ES (formerly at AFCRL). In addition, the energy-angle spectra has been determined for photons exiting collimators used with these sources. These spectra may be helpful in understanding the responses of devices and materials irradiated by the source photons.

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Gamma Energy Spectra for the RADC/ES* Cobalt 60 Sources

1. INTRODUCTION

Extensive use has been made of high intensity cobalt 60 gamma sources to investigate radiation effects in devices and materials. It is well known that such sources produce a broad energy spectrum of radiation and that materials and devices can be extra sensitive to particular portions of the spectrum. The spectrum of radiation is dependent on the mass and geometry of the source and needs to be determined for each manifestation of these parameters. We have found it necessary in several cases to know the spectra of our sources in order to interpret some of our experimental results.[1-4]

The sources employed at the former AFCRL and at RADC are composed predominately of cobalt, steel, and aluminum. The 1.32 and 1.17 MeV photons generated in the ^{60}Co nuclear decay are scattered, degraded, and attenuated

(Received for publication 3 April 1979)

*Formerly called the AFCRL Cobalt 60 sources.

1. Wall, J.A., and Burke, E.A. (1970) IEEE Trans. Nuc. Sci. NS-17:305.
2. Frederickson, A.R. (1976) IEEE Trans. Nuc. Sci. NS-23:1867.
3. Long, D.M., and Swant, D.H. (1974) Dose Gradient Effects on Semiconductors, AFCRL-TR-74-0283, AD B002055.
4. Wall, J.A., and Burke, E.A. (1974) Dose Distributions at and Near the Interface of Different Materials Exposed to Cobalt-60 Gamma Radiation, AFCRL-TR-75-0004, AD A010427.

primarily by the compton process and secondarily by the photoelectric process in such materials. Fluorescence photons are, therefore, not included in the spectra calculations. The geometries of the sources are such that an "average" ^{60}Co photon generated in the sources has a probability greater than 0.20 for scattering before leaving the source material. Many of the resulting secondary compton photons are in the 0.2 MeV energy region where they produce enhanced photoelectric effects in irradiated experiments.

The spectrum calculations were made using a computer code called "Collimator."[5] This code has been designed for sources with geometry "similar" to ours and has been compared with experimental measurements using NaI scintillators.[6] It may now be the case that such monte carlo codes are more accurate photon spectrum predictors than is an experimental measurement under high intensity irradiation, because of the difficulty of characterizing and uniquely unfolding the response of appropriate detectors. It is far more costly and no more accurate to measure the spectra by experimental means than it is to calculate it using a computer code. For a comprehensive review of MeV photon transport and effects, see Jaeger[7] and Leipunskii, et al.[8] For examples of spectra measurements by detectors, see Dardis and Scofield,[9] Scofield and Haggmark,[10] and Wechselberger.[11]

Several sources have been used and spectrum calculations have been made for each of them. In the next section, we will describe each source and the calculation scheme used to obtain its spectrum.

---

5. Morris, E.E., and Chilton, A.B. (1967) Monte Carlo Calculation of the Spectrum of Gamma Radiation from a Collimated Co-60 Source, NRDL TRC-68-6, Code available from Radiation Shielding Information Center, Oak Ridge, Tennessee.

6. Preiss, K. (1966) Monte Carlo Calculation of Self Shielding by Encapsulated Gamma Ray Sources, Univ. Illinois R NRSS-3 (AD 636 788).

7. Jaeger, R.G., Editor (1968) Engineering Compendium on Radiation Shielding, Vol. I., Springer Verlag Inc., NY, NY.

8. Leipunskii, O.I., Novozhilov, B.V., and Sakharov, V.N. (1965) The Propagation of Gamma Quanta in Matter, English edition by Pergamon Press, Ltd.

9. Dardis, J.G., and Scofield, N.E. (1966) Phys. Rev. 147(No. 1):280-7.

10. Scofield, N.E., and Haggmark, L.G. (1960) Penetration of Plane Normal and Plane Slant Gamma Rays Through Slabs of Aluminum and Steel II, Angular and Energy Spectra, USNRDL-TR-475.

11. Wechselberger, E. (1970) Atomkernenergie 16-12:64-70, Atomkernenergie, 16-27:146-152.

2. RESULTS

2.1 The AFCRL Source October 1967 to 19 June 1975

This source is composed of ten encapsulated ^{60}Co rods in an array described in Figure 1. The array is in a hot cell room roughly 3 m by 3 m by 4 m high. When not in use, the array is stored in a pit under the floor of the room and can be raised out of the pit by remote control. Small objects can be inserted in the center of the array for high intensity irradiations, or alternately, objects can be placed at a distance in the room for lower intensity irradiations. We wish to calculate the photon energy spectrum in the horizontal plane which intersects the center of the ten rods (the plane parallel to and equidistant from the aluminum ring and the aluminum base plate in Figure 1). The spectrum in this plane is representative of the spectra most everywhere else except directly off the ends of the rods.[6]

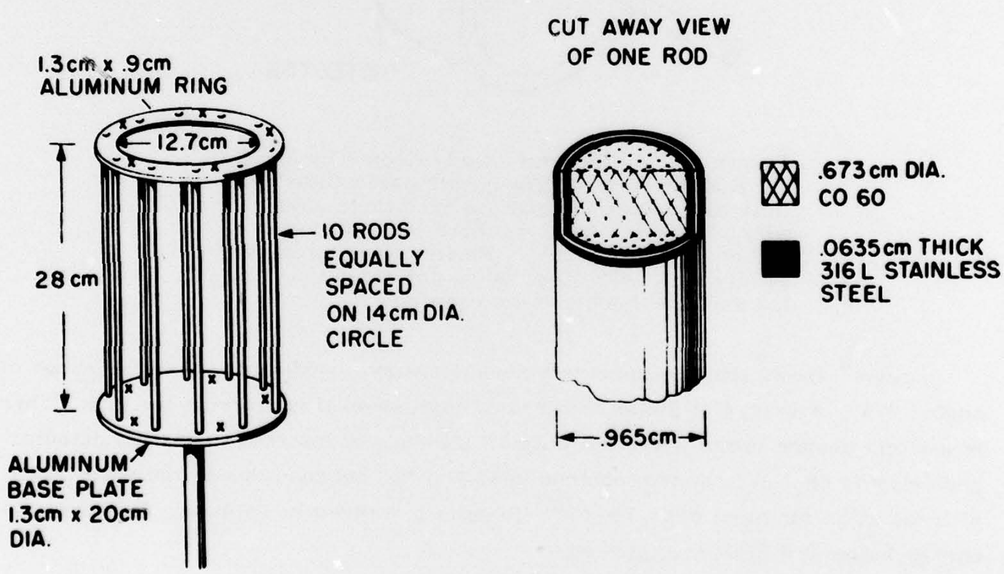

Figure 1. The AFCRL Source (1967—1975)

The collimator code[5] will calculate the energy-angle spectrum in any region wherein the region and source have cylindrical symmetry. Thus the code can be directly applied to calculating the spectrum for a rod (cylinder) source. It will not calculate the spectrum directly for an array of rods. The spectrum from the array is the algebraic sum of the spectrum from individual rods in the array, plus the spectrum of photons which are generated in one rod and scattered in another rod (once scattered photons), plus the twice scattered photons, etc. to infinite scatterings. We use the code to calculate the spectrum for one rod, and then estimate the spectrum due to scattered photons, and sum the results.

Figure 2 describes the geometry for which the code was run for one rod.

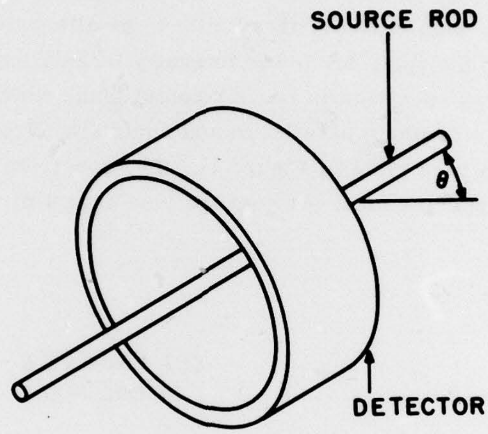

Figure 2. "Collimator" Code Geometry for Single Rod Spectrum. The monte carlo code "collimator" counts the photons (and their energy) which leave the rod, traverse the empty space, and enter the detector. Photons leaving the rod nearly parallel to the rod do not enter the detector and are therefore not counted

Preiss[6] shows that the spectrum does not vary significantly over the range of angles $\pi/4 \leq \theta \leq 3\pi/4$ at distances greater than several radii from the rod. There is a slight change in the spectrum only off the ends of the rod. Thus the detector geometry is chosen to accept photons near $\theta \simeq \pi/2$ because this is the direction of irradiation for most experiments. Results are given in Table 1. Photons with energy below 0. 1 MeV are ignored.

Table 1. Fraction of Photons ($\Delta N/N$) in Each Energy Range (ΔE, MeV) for a Single Rod Shown in Figure 1

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.388	.006	.402	.014	.014	.016	.013	.016	.020	.026	.033	.035	.017

For purposes of determining the inter-rod scattering flux (flux of photons generated in one rod and scattered in another rod), we can divide the Table 1 spectrum into two parts; photons above 1.1 MeV we call "peak" photons, and photons below 1.1 MeV we call "scattered" photons. If a peak photon is scattered by a rod it will result, with high probability, in a scattered photon with energy below 1.1 MeV. (Table 1 is an example of flux due mostly to zero or one scattering. The ^{60}Co produces equal numbers of 1.17 and 1.33 MeV photons; all other photons are scattered into lower energies. See also references 7 and 8.)

The probability that a peak photon from one rod interacts with another rod can be determined with a calculator using the rod array geometry (Figure 1) and the compton scattering cross section and is approximately 0.02. The probability that a scattered photon will interact with another rod and be lost is approximately 0.01. The probability that a scattered photon will scatter again in another rod but remain in the scattered energy range is roughly 0.02. From Table 1 we see that peak photons comprise 0.796 of a rod spectrum and scattered photons comprise 0.204. Therefore, inter-rod scattering contributes the following approximate increase in the scattered flux:

$$0.796 \times 0.02 + 0.204 \times 0.02 - 0.204 \times 0.01 \simeq 0.02$$

Thus inter-rod scattering is a two percent correction where two percent of the photons are changed from the peak to the scattered photon energy distribution. The expected error in Table 1 is greater than two percent, so we need not determine inter-rod scatter more accurately. The corrected spectrum is given in Table 2.

Table 2. Photon Energy Spectrum for the Complete Ten Rod Assembly Shown in Figure 1

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.380	.005	.394	.015	.016	.017	.014	.018	.021	.028	.036	.039	.018
probable error	.011	.002	.012	.002	.002	.002	.002	.002	.002	.003	.004	.004	.002

Errors in the spectra are caused by statistics of the monte-carlo process, uncertainty in the scattering cross-sections and uncertainty in the inter-rod scattering correction. The assumed errors are:

(a) monte carlo statistics depend on the run and in this case are ±1.2 percent in the peak, and ±7 percent for the scattered,

(b) cross section errors[12] are ±2 percent and

(c) inter-rod scattering errors are ±50 percent.

2.2 The High Specific Activity Disc, 19 June 1975 to Present

The Cobalt 60 disc source is a steel encapsulation with the Cobalt in the center. The encapsulation outer radius is approximately 3.2 cm and its thickness is 1.58 cm. A relatively small mounting clamp is not included in the calculation since it is not symmetrical and is too small to be important. Figure 3 is a schematic of the disc (not to scale).

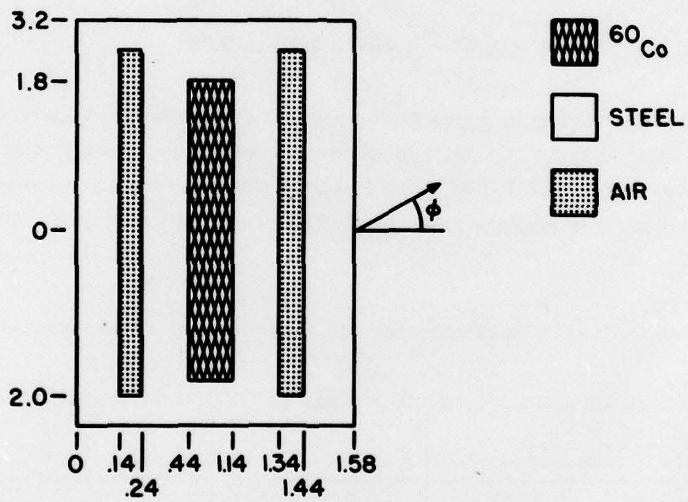

Figure 3. Schematic Illustration of the Disc Source as Used in the Computer Calculation. The radius dimension and thickness dimension are in centimeters. The drawing is not to scale and is not identical to the actual disc source

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12. Hubbel, J.H. (1977) Present Status of Photon Cross Section Data 100 eV to 100 GeV, National Bureau of Standards Special Publication 461, pgs. 3-16.

Since the disc is thicker than the previously discussed rods, we expect the disc spectrum to have a larger fraction of scattered photons. We also expect the spectrum to be less dependent on direction since the aspect ratio (maximum dimension/minimum dimension) is smaller. The spectrum was calculated at nominal angles, ϕ, of 0^{o}, 40^{o}, 80^{o} and the differences were well within the errors. The resulting spectrum is given in Table 3 and is correct for any direction.

Table 3. The Spectrum for the Disc Source Installed June 1975

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.302	.010	.307	.023	.024	.025	.027	.029	.034	.041	.057	.073	.049
probable error	.008	.002	.008	.001	.001	.001	.001	.001	.001	.002	.002	.003	.002

In this case the errors are assumed to be due to:

(a) a statistical term of 0.2 percent in the peak and 0.7 percent in the scattered,

(b) and a 2 percent term in the basic cross sections.

2.3 The Combined Source of Ten Rods and One Disc, Installed 19 June 1975

The disc is relatively small and does not scatter a significant proportion of the photons created in the rods. However, the rods scatter and degrade roughly two percent of the photons produced by the disc. We can calculate the combined spectrum by summing the two sources, each source being weighted relative to its activity level and the disc source being corrected for scattering in the rods.

The resulting spectrum is given in Table 4. The disc is mounted on the rod source in a non-symmetric manner but because the spectrum from the disc is not dependent on direction the non-symmetry is unimportant.

Table 4. The Spectrum for the Combined Disc and Ten Rod Source

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.346	.006	.356	.015	.017	.018	.017	.021	.027	.036	.050	.056	.036
probable error	.010	.002	.011	.002	.002	.002	.002	.002	.003	.004	.005	.005	.004

2.4 The Combined Source of Twenty Rods and One Disc, Installed 25 June 1976

Ten high specific activity rods were added to the previous ten rod array shown in Figure 1. The new rods are identical in size and shape to the older less active rods. The new rods are spaced on the same circumference as the older rods. Except for the increased inter-rod scattering the twenty rod array has the same spectrum as the ten rod array. The spectrum is given in Table 5.

Table 5. Photon Energy Spectrum for the Twenty Rod Array With Disc

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.368	.006	.382	.016	.016	.017	.015	.018	.023	.031	.040	.043	.024
probable error	.012	.002	.013	.002	.002	.002	.002	.002	.003	.004	.005	.005	.003

2.5 The Twenty Rod Array Source, Installed 25 June 1976

It is possible to remove the disc from the rest of the source. In that event, we need to know the spectrum for the resulting twenty rod array. This spectrum is changed from the ten rod array due to increased inter-rod scattering and the results are given in Table 6.

Table 6. The Spectrum for the Twenty Rod Array

ΔE MeV	1.34-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
$\frac{\Delta N}{N}$	.372	.006	.387	.016	.017	.018	.016	.019	.023	.029	.037	.041	.020
probable error	.012	.002	.013	.002	.002	.002	.002	.002	.003	.004	.005	.005	.003

2.6 The 6.67 Centimeter Diameter Collimator

Several experiments have been performed using a collimator with the ten rod source of Figure 1. The purpose of the collimator is to confine the photons to a particular portion of the apparatus being irradiated. However, the collimator introduces a great deal of scattered photons and we need to account for the effects due to these scattered photons. The collimator code is particularly adept at calculating the spectra for cylindrical collimators such as we use at RADC.

Figure 4 describes a cross sectional view of one collimator used to measure electron currents induced by the photon beam.[13, 14] We need to know the photon spectrum in the region of the foils. The distance between the nearest cobalt rod and the collimator is approximately 6 cm. As the figure shows, cylindrical symmetry is violated since the source is not coaxial with the cylinder so we need to modify the geometry in order to use the "Collimator Code."

The geometry modification can be made by transforming the source into a cylindrically symmetric source being careful to maintain a photon spectrum characteristic of the true rod source. The method for doing this follows.

Figure 5 pictorially describes the basic transformation — the spectrum from the rod is made identical to that from a series of carefully chosen annuli which are cylindrically symmetric with the collimator. For the proper range of angles, α, the dimensions (inner radius, outer radius and thickness) of the annuli can be chosen so that the spectrum emitted by the annuli is identical to the spectrum from the rods. All the annuli in the series were dimension adjusted so that they emitted such a spectrum, each spectrum being confirmed by use of the "collimator code."

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13. Frederickson, A.R. (1976) IEEE Trans. Nuc. Sci. NS-23:1867.
14. Pine, V.W., Chadsey, W.L., and Frederickson, A.R. (1978) IEEE Trans. Nuc. Sci. NS-25.

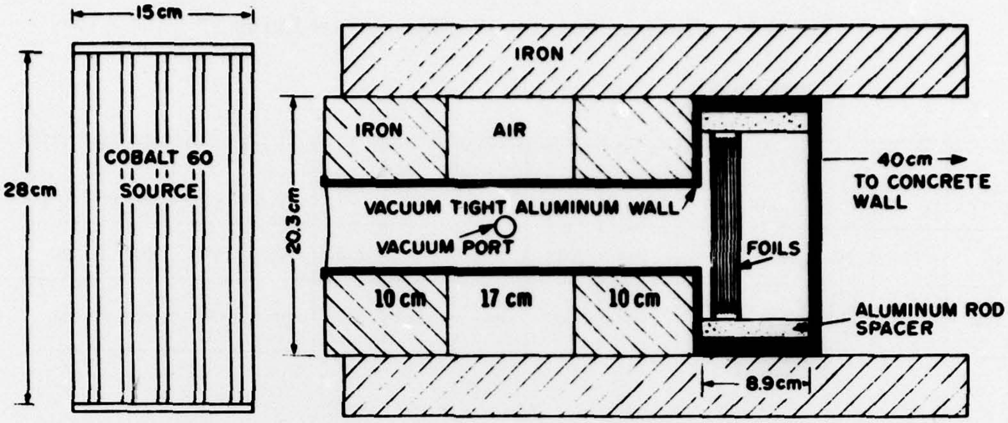

Figure 4. The 6.67 Centimeter Diameter Collimator. The collimator minimized the photon flux at the edges of the foils

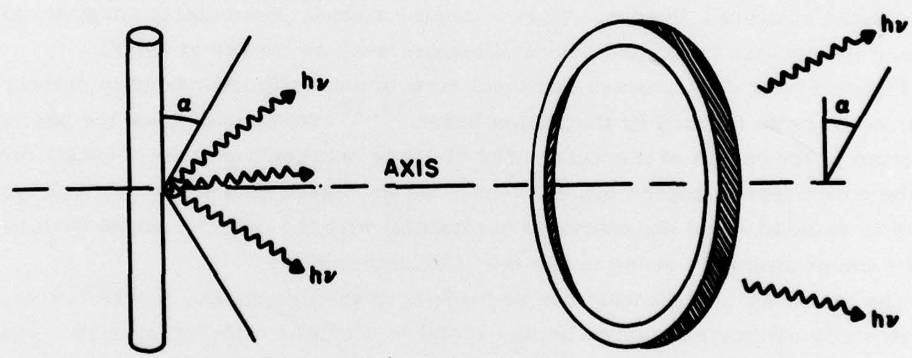

Figure 5. The Spectrum From a Rod for $20^\circ \leq \alpha \leq 160^\circ$ is Identical to That From a Properly Chosen Annulus. Note that the annulus is like a rod without an end yet not infinite in length, therefore, for $\alpha < 20^\circ$ their spectra differ

It turned out that annuli with thickness and width approximating but slightly less than the rod diameter produced the correct spectrum.

A series of annuli is needed to properly simulate the shape of the ten rod source. We have seen that inter-rod scattering is a small effect; with the collimator, which is a massive object, inter-rod scattering is a negligible effect. But the spectrum transmitted through the collimator may depend on the position of the source, so we need to use annuli which simulate the entire spatial region of source rods. Figure 6 describes how one annulus simulates photons originating from a region of the source. We can cover the entire source by using many annuli covering the range of radii from zero to 14 cm. We then weight the total emission from each annulus according to the fraction of the real array covered by the annulus (dark portion shown in Figure 6). We run the collimator code separately for each one of the annuli (the annuli are 0.94 cm thick and 0.88 cm wide so there are a total of $\frac{14 \text{ cm}}{0.88 \text{ cm}} \approx 16$ annuli to cover the real array area) placed coaxially with the collimator and spaced 8 cm in front of the collimator (see Figure 4). The spectrum in the foil region behind the collimator resulting from each annulus is weighted according to the dark area shown in Figure 6. The total spectrum is the sum of the 16 weighted spectra.

Table 7 describes the spectrum for the apparatus shown in Figure 4 and reported in references 13 and 14. The angular distribution is given since it reflects the effectiveness of the collimator whose purpose it is to create a collimated beam of photons. ∅ is the angle relative to the collimator center axis. The probable error in Table 7 would be similar to errors previously given in Table 2 for the totals over cos ∅ but the errors in particular angular bins have not been determined.

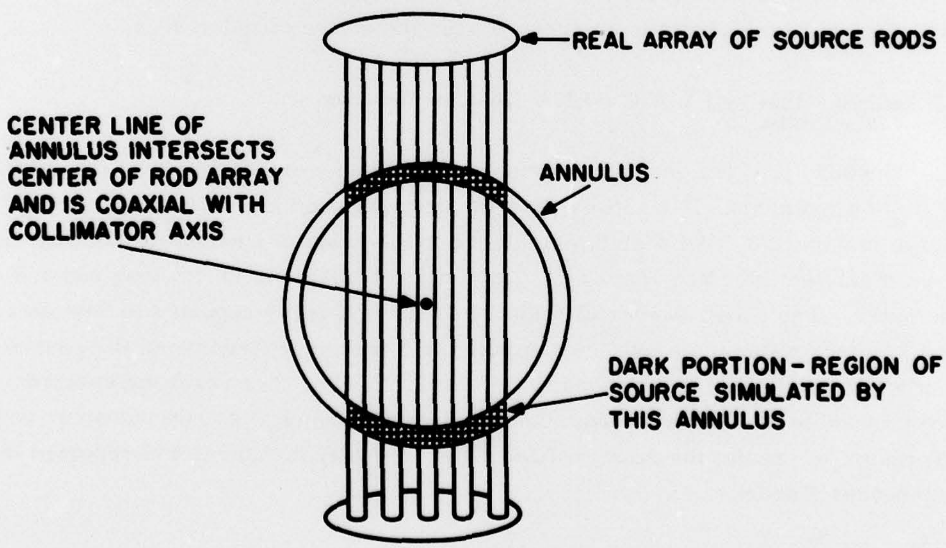

Figure 6. Simulation of a Portion of the Source by One Annulus

Table 7. Photon Energy Spectrum in a 13 cm Diameter Circle Behind the Collimator of Figure 4 (in the Region of the Foils)

hν MeV / cos ∅	1.4-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
1.0-.95	.2366	.0161	.2517	.0322	.0288	.0272	.0269	.0216	.0165	.0222	.0273	.0318	.0214
.95-.85	.0009	.0014	.0043	.0093	.0138	.0123	.0111	.0086	.0068	.0066	.0068	.0074	.0101
.85-.70	0	0	0	.0015	.0025	.0083	.0125	.0109	.0056	.0055	.0061	.0069	.0101
.70-.40	0	0	0	0	.0002	.0009	.0033	.0066	.0094	.0084	.0074	.0093	.0106
.40-0	0	0	0	0	0	0	0	.0003	.0016	.0043	.0024	.0027	.0031
Total over cos ∅	.2375	.0175	.2561	.0430	.0453	.0486	.0537	.0481	.0399	.0470	.0500	.0581	.0553

It is interesting to plot the intensity of the photon beam as a function of distance from the collimator axis in the plane of the foils. We have not made such a calculation with the collimator code but we have used a 1 cm diameter ionization probe ("Radocon" by Victoreen Corp.) to measure the intensity profile in the plane of the foils; Figure 7 describes the results. Incomplete evidence indicates that the spectrum, shown in Table 7, holds true everywhere within the 13 cm diameter circle even though the spectrum is an average over the entire circular area.

2.7 Collimator Used by J.A. Wall and E.A. Burke for Measuring Dose Profiles

The dose profiles described in references 1 and 4 are sensitive to the spectrum of irradiation photons. A different collimator was used in these measurements as shown in Figure 8. We wish to calculate the spectrum of photons irradiating the 5 cm diameter interface chamber. The steel collimator is 20 cm long and 3.8 cm diameter. The cobalt source in Figure 8 is the rod array reported in Section 2.1 and Figure 1 above. We use the computational technique (transform the source into a series of annuli) described in Section 2.6 above: The resulting spectrum is given in Table 8. This spectrum can be used in a photon/electron transport code to attempt to predict the dose profiles experimentally measured and reported in references 1 and 4.

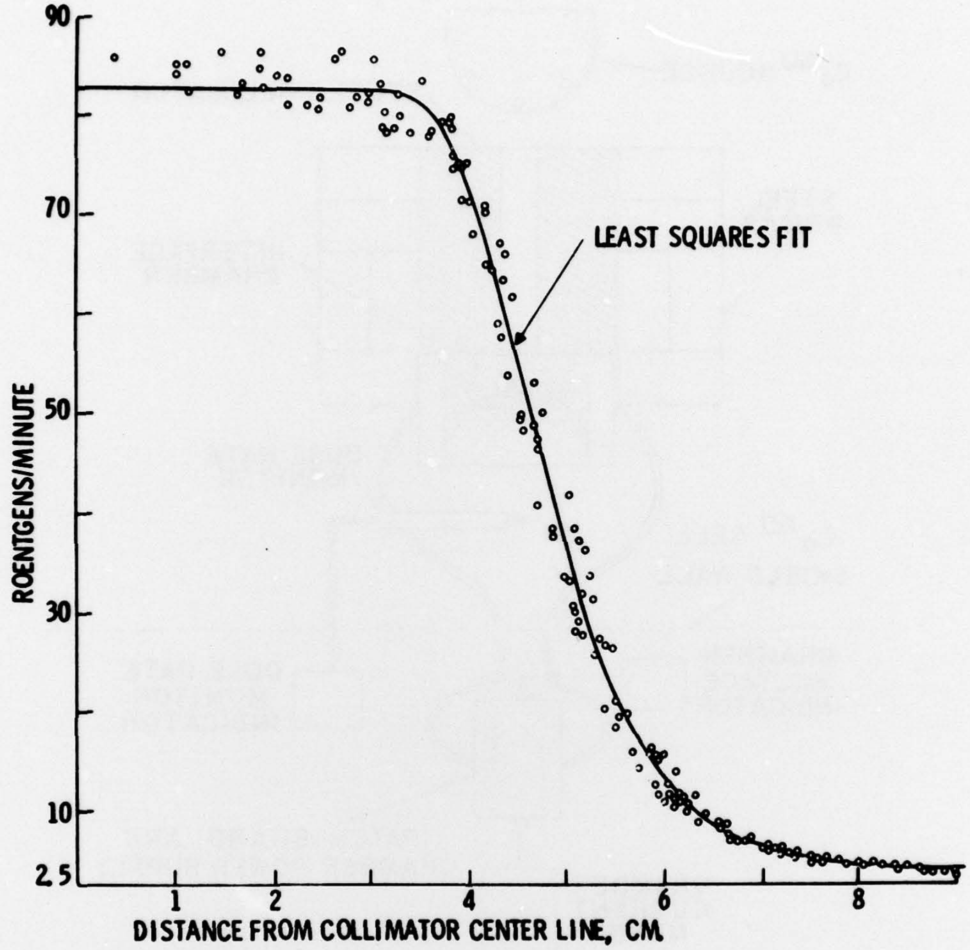

Figure 7. Radial Dependence of ^{60}Co γ Intensity in the Plane of the Foils Shown in Figure 4. The least squares fit function is $\dot{R} = 82.69 - 78.52 \exp(-189.9 \exp(-0.8676\, r^{1.189}))$, $\dot{R}$ is Roentgens per minute, r is radial distance in centimeters

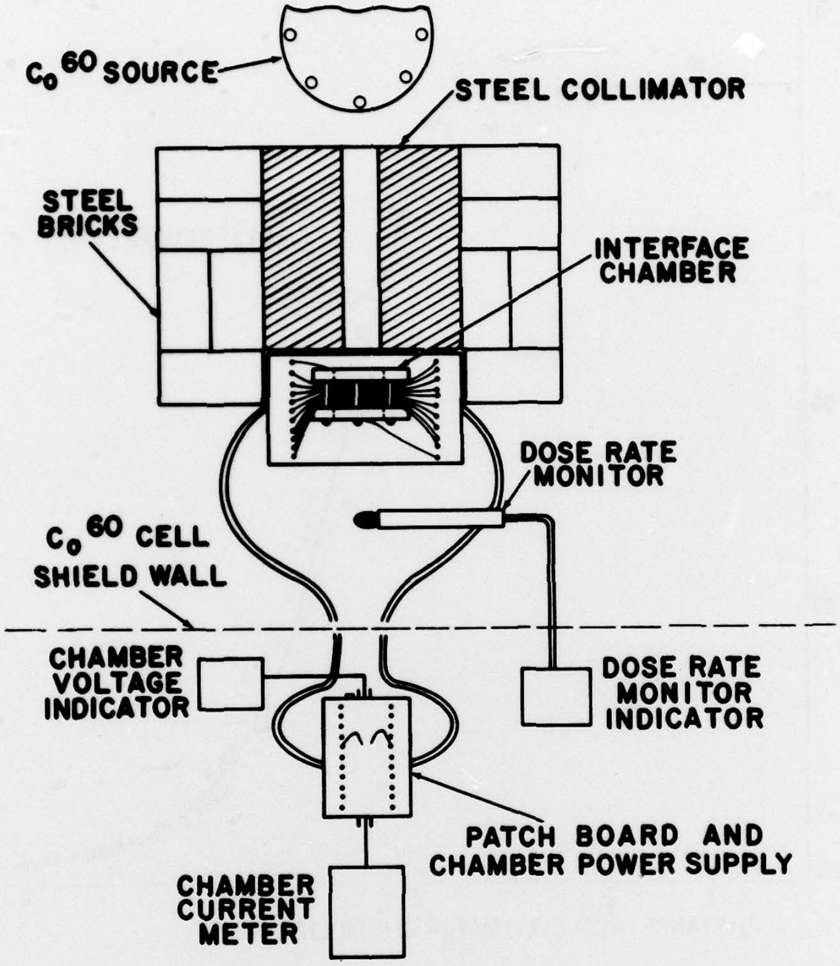

Figure 8. Schematic for Irradiation Geometry of J. A. Wall

Table 8. Photon Energy Spectrum Irradiating the Interface Chamber of Figure 8 and References 1 and 4. ∅ is the Angle Relative to the Collimator Center Axis

hν MeV / cos ∅	1.4-1.3 (1.33)	1.3-1.2	1.2-1.1 (1.17)	1.1-1.0	1.0-.9	.9-.8	.8-.7	.7-.6	.6-.5	.5-.4	.4-.3	.3-.2	.2-.1
1.0-.95	.280	.017	.306	.040	.050	.030	.041	.019	.021	.028	.032	.039	.027
.95-.85	0	0	0	.004	.006	.009	.004	.007	.003	.004	.009	.007	.005
.85-.70	0	0	0	0	0	0	0	0	0	0	.001	.007	.003
.70-.40	0	0	0	0	0	0	0	0	0	0	0	0	.001
.40-0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total over cos ∅	.280	.017	.306	.044	.056	.039	.045	.026	.024	.032	.042	.053	.036

3. COMMENTS

It is instructive to compare these results with experimental and computational results for other gamma sources published in the literature. For this purpose, see references 15, 16, and 17 and references contained therein. An extensive literature exists for transport through shields with and without ducts or voids; however, the published results generally are in terms of exposure intensity rather than energy spectra. Energy spectra for pure shields are available in some cases[7-10] and can be compared to these results.

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