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Concrete as a Protective Barrier for Gamma Rays from Cobalt-60

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The broad-beam and narrow-beam attenuation of Co^{60} gamma rays has been investigated experimentally, and the data are presented here. In protective barriers the geometry necessarily requires the use of broad-beam attenuation curves to determine the required barrier thickness. This paper presents attenuation curves for lead, concrete, and steel necessary for determining the required protection for any particular cobalt source in storage or transportation. There is also included a table for shielding requirements for Co^{60} sources of 10 millicuries to 2 curies.

I. Introduction[1]

Three distinct processes are effective in the attenuation of gamma rays; photoelectric absorption, Compton absorption and scattering, and pair production. In each of these three modes of interaction of gamma rays with matter, the gamma ray gives up all or part of its initial energy to the atom. Each of these processes gives rise to some secondary photons of energy less than that of the primary photons and in a direction different from that of the primary photon. These secondary radiations are (a) characteristic radiation of photoionization, (b) Compton scattered photons and (c) annihilation radiation in the loss of an electron-positron pair. However, in the energy range under consideration (1.1 and 1.3 Mev) the soft characteristic radiation is readily absorbed, and the annihilation radiation is negligibly small. Therefore, all of the photoelectric, Compton absorption, and pair-production phenomena may be considered as true absorption of photon energy because the probability that secondary electrons will produce "bremsstrahlung" is very small.

As the Compton-scattered photons are always produced during the attenuation of a beam of gamma rays, the geometry of the experimental arrangement for measuring attenuation may be very important. The geometry can be classified as narrow beam,[2] or good geometry; and broad beam (see footnote 2) or bad geometry. The narrow-beam attenuation is obtained under conditions in which only a negiligible amount of the scattered radiation is measured by the chamber. Under experimental conditions, this amounts to having the irradiated area of the absorber subtend a small solid angle at the chamber as well as the source. This condition can be verified experimentally by a check on the inverse square law for the radiation received by the chamber. If the inverse square relation is found to hold, the scattered radiation from the barrier is negligible. If, however, the chamber is situated near the emergent side of the absorber and the irradiated area is large compared to the dimensions of the chamber, or if the barrier is very near to the source there will be an appreciable portion of the chamber ionization produced by the secondary radiation from the absorber and a broad-beam condition will exist. For this condition the attenuation curve is unique only for that particular barrier-to-chamber distance and barrier-to-source distance.

The ionization measured by the chamber may be thought of as being due to radiation from two different sources; (A) that part of the radiation that comes directly from the source as primary radiation, (B) the remainder that comes from the entire irradiated volume of the absorber as secondary radiation. Several factors serve to limit the effective volume, which acts as a secondary source. The path length of the incident plus the scattered-photon in the absorber will be greater

[1] The work described here was supported in part by the Atomic Energy Commission.

[2] H. O. Wyckoff, R. J. Kennedy, and W. R. Bradford, J. Research NBS **41**, 223 (1948) RP1920.

for oblique rays and, therefore, such photons have a greater probability of being absorbed. In addition the angle between the incident and the scattered photon must be greater for oblique rays and hence the photon energy smaller. This latter factor also increases the probabilityof true absorption of the photon.

The increase in dosage rate of the broad beam over the narrow beam is due to the large amount of scattered radiation in the attenuated broad beam and to the increased spectral sensitivity of the ion chamber for the very low energy scattered radiation. As the absorber thickness is increased from zero, there is at first an over-all increase in the ratio of the number of emergent secondary photons to the emergent primary photons. The secondary photons originate mainly through Compton scattering, and their energy is dependent on the angles through which they have been scattered. Another possible phenomenon that would increase the dosage rate when scattered radiation is measured was recently discussed by Failla.[3] He pointed out that the ionization produced in the chamber is proportional to the photon energy and the absorption coefficient in air, and that the absorption coefficient increases very rapidly as the photon energy is decreased below 70 Kev. The Compton photons having energy below this value may produce a greater effect in the chamber than the primary photon. Such scattered photons would, however, have to be of an energy below 30 Kev in order to produce such an effect for million-volt primary radiation.

These softer scattered secondaries are more readily attenuated by the absorber than the primary radiation, and eventually an absorber thickness is reached at which the production of new secondaries is just balanced by their absorption in the added thickness. This effect is observed as a slight increase in dosage rate for thin absorbers and the divergence of the narrow- and broad-beam attenuation curves. The attenuation curves will be concave downward for small absorber thicknesses and are expected to become parallel to the narrow-beam curves for very large thicknesses of absorber. The range of shielding thicknesses studied here was not sufficient to obtain this equilibrium condition. The above effect is seen to be much less for lead than for lighter materials such as concrete and steel, due to the difference in the photoelectric absorption of the secondary photons in these materials.

II. Description of Apparatus

Figure 1 shows the experimental arrangement. The measuring device used in this work was a cylindrical ionization chamber with ⅛ in. thick Bakelite walls, approximately 10 cm in diameter

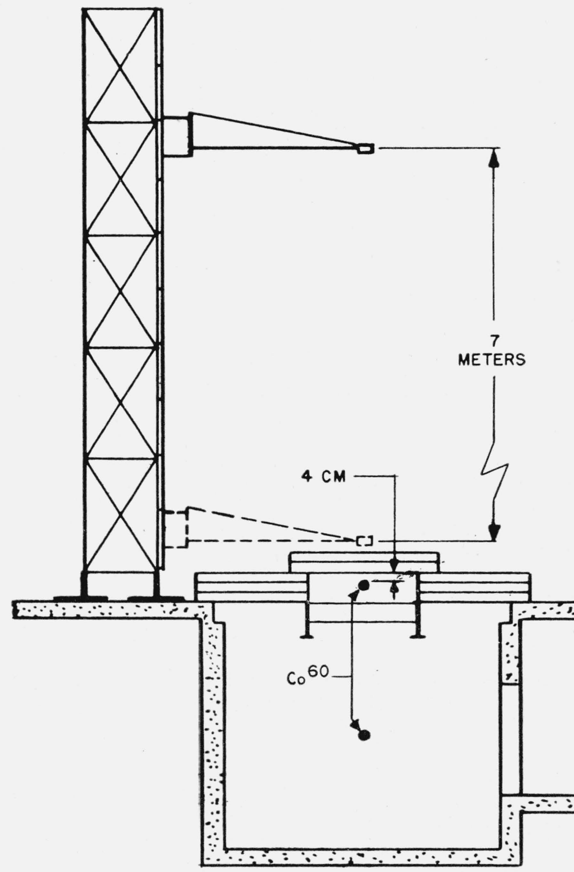

FIGURE 1. *Experimental arrangement for broad-beam attenuation measurements of gamma rays from Co^{60}.*

and 10 cm in length containing 824 ± 2 cc of free air. The collecting potential was 400 v, which was well above that required for saturation. The chamber was attached to one end of a 10-ft duralumin tube, the other end being connected to a brass cylinder housing the split FP–54 electrometer tube and a selection of S. S. White grid resistors ranging from 10^8 to 10^{11} ohms.

The electrometer tube housing was supported on a movable carriage that could travel in elevation through a distance of 7 m. The duralumin

[3] G. Failla, Am. J. Roentgeol. Radium Therapy **54,** 553 (1945).

tube could also be rotated about a vertical axis through the carriage through 120°. The elevation and azimuth motions were controlled by remote switching. A pair of selsyns indicated the position of the chamber. As a check on the positioning of the chamber, a cathetometer was used over the first meter of elevation. Its reading showed a consistent repetition of the elevation within 3 or 4 mm of the position indicated by the selsyns.

The source of radiation was a cylinder of solid cobalt-60, 1 cm in diameter and 1½ cm in length

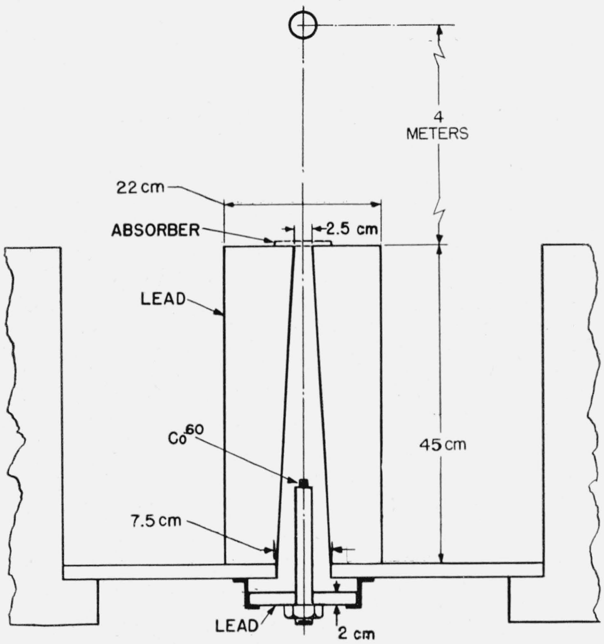

FIGURE 2.—*Experimental arrangement for narrow-beam attenuation measurements.*

with an apparent activity of approximately 1.75 curies. It was enclosed in a capsule of duralumin 1 mm thick for convenience in handling and as a protection against possible contamination of the building. The source was then placed on a supporting rod that could be moved over a range of 4-m elevation in a pit 16 by 16 by 14 ft deep. The pit was covered with 18 in. of concrete except for a center opening 6 by 6 ft. This opening was further reduced to 4 by 4 ft by placing ¼ in. of lead over the outer edge of the pit.

In the narrow-beam attenuation determination, figure 2, a lead shield 22 cm in diameter and 45 cm long, with a conically shaped center hole converging from 7.5 to 2.5 cm in diameter, was used to diaphragm the radiation. This shield was placed vertically in the center of the pit opening so that the absorbers could be placed directly on top of the limiting aperture. The irradiated area of the absorber was 2.5 cm in diameter. The lead, copper, and tin absorbers used here were 15 cm square and 2 to 10 mm thick. The concrete absorbers were 4- and 6-in. diameter cylinders 4 to 8 in. long with a density of 2.35 g/cm^3. The steel absorbers were 30 cm square and 1.27 cm thick.

A separate experiment, based on the inverse square criterion mentioned above, was designed to prove that this arrangement provided narrow-beam attenuation data. The chamber was placed axially 2 m from the absorber, and the distance from the source of the limiting aperture varied within the shield. Moving the source over the range of 10 to 37 cm from the limiting aperture showed no change in the dosage rate at the chamber that could not be accounted for by the inverse square law. The cobalt was then placed at a fixed distance of 26 cm from the limiting aperture, and the chamber-to-source distance was varied through a range of 0.4 to 7 m. Over the range of 1.5 to 7 m, there was no appreciable change in the dosage rate at the chamber other than the inverse square variation. With the chamber fixed at 4 m from the limiting aperture the above results indicated, therefore, that the amount of scattered radiation measured by the chamber was negligible and that the narrow-beam condition existed.

For the broad-beam measurements the source was undiaphragmed and placed at a distance of 4 or 210 cm from the bottom of the absorbers. The concrete absorbers were blocks 8 ft by 8 ft by 6 in. thick weighing approximately 2.5 tons each. The steel absorbers were sheets 8 by 8 ft with thicknesses of ⅛, ⅜, and ½ in. The lead absorbers were 2 ft by 8 ft by ⅛ in. thick and overlapped ¼ in. at the joints. No joint was closer than 10 in. to a line through the center of the source and chamber. The lead, being quite flexible, required additional support, so ¾-in. plyboard was placed over the pit leaving an unsupported area 3 by 3 ft.

The split FP–54 electrometer was used as a null indicating system in a circuit recommended by the manufacturer. The values of the compensating voltage, grid leak resistance, chamber volume, temperature, pressure, and air wall correction [4] served to determine the dosage rate at

[4] G. C. Lawrence, Can. J. Research [A], **15**, 67 (1937).

the chamber. All dosage measurements were referred back to a distance of 1 m from the source. The grid leak resistance values were determined by calibrating a 10^9 ohm resistance and then making frequent intercomparisons. The unknown resistances were then determined from the comparison ratios.

III. Results

An auxiliary experiment was performed to determine the amount and the effect of extraneous scattering from the pit walls and floor. The source was suspended 138 cm below the chamber, so that the chamber-to-source distance was fixed. The source and chamber were moved together in elevation up to a distance of 7 m above the floor. The dosage rate gradually decreased and became constant for elevations above 3 m. Since the source-to-chamber distance was roughly one-fifth the distance to the nearest wall, the wall scattering is considered negligible. This dosage rate corrected by the inverse square law to 1 m, was taken as the number of roentgens per hour at 1 m for this particular source.

TABLE 1. *Experimental narrow-beam attenuation data for gamma rays from cobalt*

Material	Atomic number Z	Atomic weight, A	Z/A	μ/ρ	$\mu A/\rho Z$[a]
Concrete	----	------	0.50	0.055	0.111
Steel	26	55.85	.465	.054	.115
Copper	29	63.57	.456	.052	.115
Tin	50	118.7	.422	.050	.119
Lead glass, 65% PbO and 8% BaO	----	------	.433	.059	.136
Lead	82	207	.396	.057	.144

[a] μ/ρ is the mass absorption coefficient in cm² gram; μ is the linear absorption coefficient in centimeters^{-1}; and ρ is the density of the material in gram cm^{-3}.

Measurements taken without absorbers and at various positions of the source showed deviations from the inverse square law. The comparison between the inverse square values and the value determined by the auxiliary experiment indicates that the scattering varies from 2 percent with the source at the top of the pit and the chamber 40 cm above the pit, to 8 percent with the source moved down to 210 cm from the top of the pit. Thus the scattering correction applied to those points determining the attenuation curves reported here was 2 percent. The experimental error is considered to be approximately ± 5 percent.

Figure 3 shows the broad-beam attenuation curves for lead, steel, and concrete. The distance from the chamber to the emergent side of the barrier is 40 cm and the source-to-barrier distance is 4 cm. As a comparison, two points from data previously obtained by Robertson [5] have been included on the broad-beam curve for lead. These data, taken with cylindrical lead shields enclosing the entire source, are expected to be

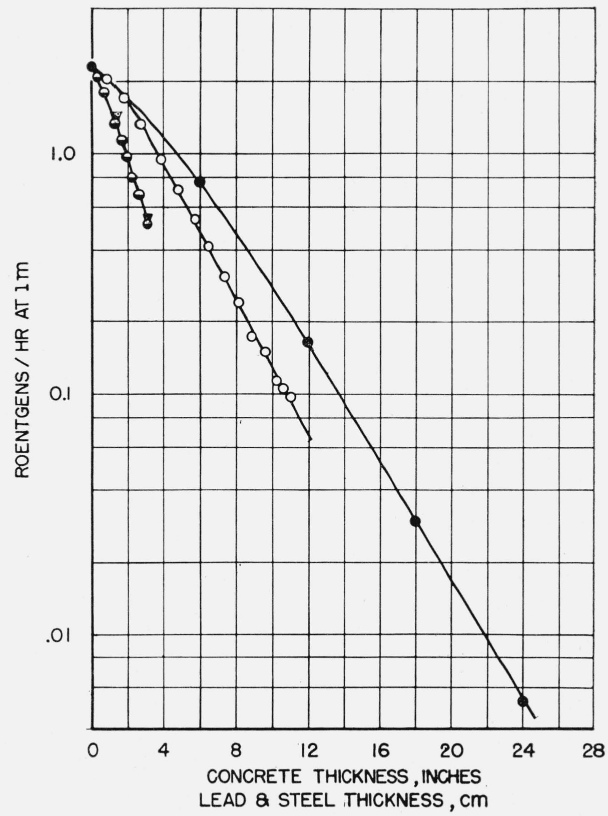

FIGURE 3. *Broad-beam attenuation curves for gamma rays from Co^{60}.*

●, Concrete; ◒, lead, ○; steel; ▼, Robertson's lead curve.

higher due to the side-scatter and back-scatter from the lead shields. It is seen that these points are about 3 percent higher than the data reported here. The narrow-beam data, table 1, indicates that there is little difference in the photoelectric absorption in concrete and steel. On the basis of mass per unit area, the concrete and steel attenuation curves are the same. It is expected that materials of atomic number between steel and concrete would also follow the same attenuation curves. The broad-beam attenuation curves of

[5] K. Z. Morgan, J. App. Phys. **19**, 593 (1948).

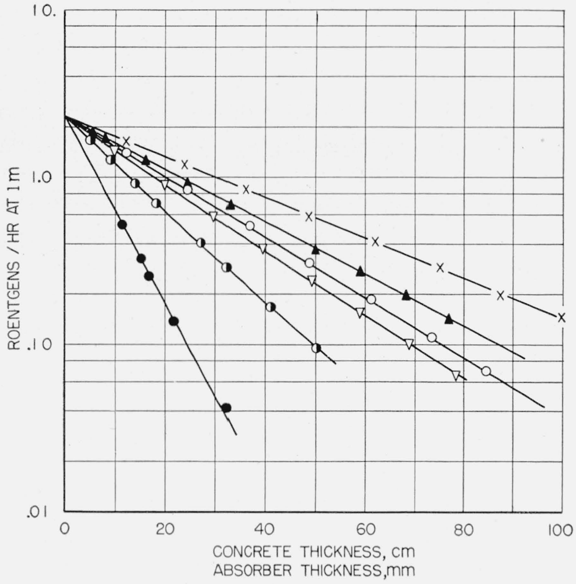

FIGURE 4. *Narrow-beam attenuation curves for gamma rays from Co.*[60]

●, Concrete; ◑, lead; ○, steel; X, lead glass; ▽, copper; ▲, tin.

figure 3 are, therefore, applicable over this range of atomic numbers provided the same mass of barrier is used.

Table 1 gives the experimental absorption coefficients determined from the narrow-beam logarithmic transmission curves of figure 4. The quantity $\mu A/\rho Z$ is proportional to the electronic absorption coefficient. This factor increases with atomic number and illustrates the importance of photoelectric absorption in materials of high atomic number. The absorption coefficients are in good agreement with those reported by Mayneord and Cipriani.[6] As an indication that the scattering measured in the narrow beam was negligible, the dosage rate observed with no absorber agreed with that obtained in the auxiliary experiment described above.

Figure 5 shows the experimental variation in dosage rate with distance between the chamber and barrier for different distances between source and barrier. All data have been computed back to a distance of 1 m from the source by the inverse square relation and also have been corrected for the scattering from the pit walls. The solid curves indicate the dosage rates measured for the two different source positions. For these measurements, 1 ft of the outer edge of the pit opening was covered with ¼ in. of lead to reduce the scattered radiation from the pit walls and 18-in. "concrete covers". The upper curve of group *A* shows that the scattering is mainly from the sides of the pit opening in that the abrupt change in slope occurs at the point where the chamber just falls into the shadow of the lead and no longer "sees" any of the sides of the pit opening. The dotted line at 2.33 roentgens/hr at 1 m is the dosage rate determined by the auxiliary experiment. The increased dosage rate above 2.33 roentgens/hr at 1 m for the source 4 and 210 cm from the top of the pit is due to the extraneous scattering and provides the basis for our scattering correction.

The slight positive slope of the upper curves of groups *B*, *C*, and *D* is due to the apparent change in beam diameter as seen by the chamber and can be explained as follows:

With the source only 4 cm from the barrier, the attenuation in the outer rings of the beam is greater due to the increased path length of the incident plus the scattered photon in the barrier

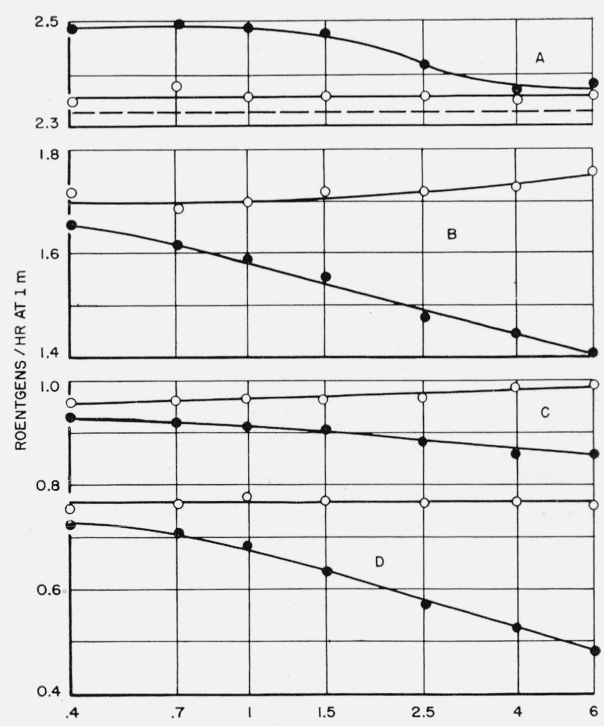

FIGURE 5. *Variation in dosage rate with distance between the chamber and barrier for different source distances.*

The inverse square correction has already been made. A, No absorber; B, 1.68 cm of steel; C, 1.9 cm of lead; D, 6 in. of concrete. Source to barrier distance: ○, 4 cm; ● 210 cm.

[6] W. V. Mayneord and A. J. Cipriani, Can. J. Research [A], **25**, 303 to 314 (1947).

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for small chamber-to-barrier distances. As the chamber-to-barrier distance increases, the path length of the incident plus the scattered photon is less so that the apparent beam diameter increases. For the greater chamber distances the angle of scattering is less and the photon energy greater, thus decreasing the apparent attenuation of the radiation.

For the lower curves of groups, *B*, *C*, and *D* with a source-to-barrier distance of 2.1 m., the effective beam diameter is essentially the same for all chamber-to-barrier distances, being controlled by the pit aperture. The predominant factor in the apparent increase in attentuation is that as the chamber moves away from the barrier, less of the scattered radiation is measured by the chamber, and thus a narrow beam condition is being approached. As previously described (see footnote 1), if the barrier-to-chamber distance is made sufficiently large these curves level off at a value corresponding to the narrow-beam data for that absorber thickness.

When the data were reduced to a distance of 1 m from the cobalt source, no attempt was made to correct for the inverse square law for the distance to the apparent barrier source, the barrier being the source of all scattered radiation.

Table 2 gives the shielding required for cobalt-60 sources at various distances. The lead requirements were taken from data obtained by Robertson as cited by Morgan (see footnote 5). The concrete requirements were obtained from the broad-beam attentuation curves figure 3, the dosage rate being reduced to the permissible rate of 300 milliroentgens per 48-hr. work week. All thicknesses are in inches.

TABLE 2. *Primary protective barrier requirements for* Co^{60}

All thickness are in inches. Column headings 1 meter, 2 meters, 3 meters indicate the relative barrier to chamber distances

Number of mc	1 meter		2 meters		3 meters	
	Lead	Concrete	Lead	Concrete	Lead	Concrete
1	0	0	0	0	0	0
10	0.70	4.9	0	0	0	0
50	1.92	10.8	0.88	5.9	0.17	1.5
100	2.41	13.3	1.40	8.3	.78	5.3
250	3.05	16.6	2.08	11.6	1.49	8.8
500	3.53	19.1	2.57	14.1	2.00	11.2
1,000	4.03	21.5	3.05	16.6	2.48	13.7
2,000	4.51	24.0	3.53	19.1	2.97	16.2

WASHINGTON, September 7, 1949.