



*Technical Note*

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**PENETRATION OF GAMMA  
RAYS FROM ISOTROPIC  
SOURCES THROUGH  
ALUMINUM AND CONCRETE**



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**U. S. DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS**

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# NATIONAL BUREAU OF STANDARDS

## *Technical Note*

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MAY 11, 1959

### **PENETRATION OF GAMMA RAYS FROM ISOTROPIC SOURCES THROUGH ALUMINUM AND CONCRETE**

Martin J. Berger and Lewis V. Spencer

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Penetration of Gamma Rays from Isotropic Sources through Aluminum  
and Concrete

Martin J. Berger and Lewis V. Spencer

ABSTRACT

Semi-analytical expressions, with numerically specified parameters, are given which represent the gamma ray dose distribution in infinite aluminum or concrete media, for sources that are monoenergetic (with energies between 10.22 Mev and 0.0341 Mev), isotropic, and have the form of an infinite plane, point, disk or spherical surface.

1. Introduction

This publication presents recent results of a program of gamma ray penetration calculations now in progress at the National Bureau of Standards.<sup>1/</sup> This program is based on the use of the moment method.<sup>2/</sup>

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<sup>1/</sup> Previous unpublished reports on this program include: J. H. Hubbell, Dose due to distributed gamma ray sources, November 1956. L. V. Spencer and J. C. Lamkin, Slant penetration of gamma rays in water, July 1958.

L. V. Spencer and J. C. Lamkin, Slant penetration of gamma rays; mixed radiation sources, February 1959.

<sup>2/</sup> L. V. Spencer and U. Fano, J. Res. NBS 46, 446 (1951). See also U. Fano, L. V. Spencer and M. J. Berger, Encyclopedia of Physics, 38, II, Springer, Berlin, July 1959.

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It provides basic information about the attenuation of radiation in extended homogeneous media, which is needed for Civil Defense shielding studies.

The present report deals with the penetration of gamma rays from isotropic sources through aluminum or concrete. The physical quantity computed is the gamma ray dose as a function of the distance from the source. The results apply to all types of isotropic sources (plane or point sources, disk sources, spherical sources, etc.).

The dose as function of the distance from a point-isotropic source has previously been calculated.<sup>3/4/</sup> The new calculations differ from this work

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<sup>3/</sup> H. Goldstein and J. E. Wilkins, Jr., AEC Report NYO 3075 (1954).

<sup>4/</sup> Unpublished report, J. H. Hubbell, Dose due to distributed gamma ray sources, November 1956.

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in the following respects: (a) A wider range of monoenergetic sources is treated, extending from 10.22 Mev down to 0.0341 Mev. (b) The results are presented in semianalytical form, with numerically specified parameters, rather than in completely numerical form. This has the advantage that the basic calculation, for a plane isotropic source, can readily be applied to other source types by simple analytical manipulations.

## 2. Plane Isotropic Source

Notation:

$E_o$  = source energy

$z$  = distance from source plane

$\mu(E)$  = gamma ray attenuation coefficient;  $\mu_o = \mu(E_o)$

$\mu_{en}(E)$  = energy absorption coefficient for air

$K_{PL}$  = source strength: number of gamma rays emitted per second  
from a unit area of the source plane

$E_1(z) = \int_z^\infty (e^{-s/s}) ds = \text{exponential integral}$ <sup>5/</sup>

$D_{PL}(z) = \text{absorbed air dose}$ <sup>6/</sup> at a distance  $z$  from the source plane.

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<sup>5/</sup> For a tabulation of the exponential integral, see, e.g., Tables of Sine, Cosine and Exponential Integrals, WPA, 1940.

<sup>6/</sup> For a definition of absorbed dose, see Nat. Bur. of Standards Handbook 62, Report of the International Commission of Radiological Units and Measurements (1956).

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The absorbed air dose can be represented by the following formula:

$$D_{PL}(z) = \frac{1}{2} K_{PL} \mu_{en}(E_o) E_o E_1(\mu_o z) + \frac{1}{2} K_{PL} \mu_{cn}(E_o) E_o \left\{ A_1 e^{-B_1 \mu_o z} + A_2 e^{-B_2 \mu_o z} \right\} \quad (1)$$

If  $E_0$  is expressed in units of 100 ergs,  $\mu_{en}$  in  $\text{cm}^2/\text{g}$ ,  $K_{PL}$  in  $\text{cm}^{-2}\text{sec}^{-1}$ , and  $z$  and  $\mu_0$  in reciprocal but otherwise arbitrary units, then  $D_{PL}(z)$  has units of  $\text{rads}^{7/}\text{sec}^{-1}$ . The first and second term in (1) represent

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$7/$  1 rad corresponds to an energy absorption of 100 ergs per gram of the medium (in the present case air).

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the contribution to the dose by unscattered and scattered gamma rays, respectively.

The dose depends on the atomic number of the medium primarily through the attenuation coefficient  $\mu_0$ , and much less sensitively through the parameters  $A_1$ ,  $A_2$ ,  $B_1$  and  $B_2$ . The atomic number of aluminum ( $Z = 13$ ) is close to that of concrete ( $Z_{\text{effective}} \sim 13.4$ ) so that the same set of parameters can be used for both materials. Table 1 lists these parameters (obtained through a moment calculation for aluminum) for various source energies. Also shown are the energy absorption coefficient for air, and the attenuation coefficients for aluminum and concrete. The latter two quantities, when expressed in  $\text{cm}^2/\text{g}$ , are very close to each other.



### 3. Other Source Geometries

There are simple relations between the dose distributions for different source geometries<sup>8/</sup> and which hold under the following conditions:

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<sup>8/</sup> Cf. Reactor Handbook, Vol. I, Chapter 2.5, AECD 3645 (1955).

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- (a) The detector and source are isotropic. (b) The medium is homogeneous.  
(c) The boundaries are far enough removed to be unimportant. We shall apply a few of the more important of these relations.

#### 3.1. Point Isotropic Source

Notation:

$r$  = distance from point source

$K_{PT}$  = source strength: number of gamma rays emitted per second

$D_{PT}(r)$  = absorbed air dose at a distance  $r$  from the source

The general relation between point- and plane-source distributions is

$$D_{PT}(r) = \frac{1}{2\pi r} \left[ \frac{d}{dz} D_{PL}(z) \right]_{z=r}. \quad (2)$$

By applying this relation to Eq. (1) and inserting the appropriate source normalization constant we find that

$$D_{PT}(r) = \frac{K_{PT}\mu_{en}(E_o)E_o}{4\pi r^2} e^{-\mu_o r} + \frac{K_{PT}\mu_{en}(E_o)E_o}{4\pi r^2} \mu_o r \left\{ A_1 B_1 e^{-B_1 \mu_o r} + A_2 B_2 e^{-B_2 \mu_o r} \right\}. \quad (3)$$

If  $r$  is expressed in cm,  $K_{PT}$  in  $\text{sec}^{-1}$ , and the units for the remaining quantities are the same as in the case of the plane source problem, then  $D_{PT}(r)$  again represents a dose in  $\text{rads sec}^{-1}$ .

From Eq. (3) one can derive an expression for the dose build-up factor  $B(r)$  (ratio of the total dose to the dose contributed by unscattered radiation). We find that

$$B(r) = 1 + \mu_o r \left\{ A_1 B_1 e^{-(B_1-1)\mu_o r} + A_2 B_2 e^{-(B_2-1)\mu_o r} \right\}. \quad (4)$$

This expression may be compared with results previously obtained by Goldstein and Wilkins.<sup>3/</sup> According to Figure 1 which contains plots of  $B(r)$  vs.  $E_o$ , for different values of  $\mu_o r$ , the two sets of calculations are in good agreement, insofar as they cover the same range of source energies. This is interesting in view of the fact that the methods of calculation differ. Both make use of the numerical flux moments, calculated according to identical

equations, but the construction of the flux from the moments was done differently. Goldstein and Wilkins used the method of polynomial expansion developed in Reference 2. The present calculations are based on a technique called "function-fitting"<sup>2/</sup> which we believe to be

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<sup>2/</sup> Described in the Encyclopedia article mentioned in footnote 2.

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somewhat more accurate, and which leads to a representation of the type of Equation (1) which is convenient for analytical manipulations.

### 3.2. Isotropic Disk Source

Notation:

$a_1$  = radius of disk source

$z$  = distance from source along axis of disk

$K_{\text{DISK}}$  = source strength: number of gamma rays emitted per second from a unit area of the disk

$D_{\text{DISK}}(z, a)$  = absorbed air dose at a point on the axis of the disk, at a distance  $z$ .

Using the general relation

$$D_{\text{DISK}}(z,a) = 2\pi \int_z^{\sqrt{z^2+a^2}} D_{\text{PT}}(r) r dr \quad (5)$$

and the appropriate source normalization, we obtain the result

$$\begin{aligned} D_{\text{DISK}}(z,a) = & \frac{1}{2} K_{\text{DISK}} \mu_{\text{en}}(E_0) E_0 \left\{ E_1(\mu_0 z) - E_1(\mu_0 \sqrt{z^2+a^2}) \right\} + \\ & + \frac{1}{2} K_{\text{DISK}} \mu_{\text{en}}(E_0) E_0 \left\{ A_1 \left[ e^{-B_1 \mu_0 z} - e^{-B_1 \mu_0 \sqrt{z^2+a^2}} \right] + \right. \\ & \left. + A_2 \left[ e^{-B_2 \mu_0 z} - e^{-B_2 \mu_0 \sqrt{z^2+a^2}} \right] \right\}. \quad (6) \end{aligned}$$

With  $a$  as well as  $z$  expressed in units reciprocal to those of  $\mu_0$ , and with  $K_{\text{DISK}}$  in  $\text{cm}^{-2} \text{sec}^{-1}$ ,  $D_{\text{DISK}}(z,a)$  is in  $\text{rads sec}^{-1}$ .

### 3.3. Isotropic Spherical Surface Source

Notation:

$r_o$  = radius of spherical surface containing the source

$r$  = distance from center of sphere

$K_{SPH}$  = source strength: number of gamma rays emitted per second  
from unit area of source

$D_{SPH}(r, r_o)$  = absorbed air dose at a distance  $r$  from the center of the  
sphere.

Using the relation

$$D_{SPH}(r, r_o) = \frac{r_o}{r} \left\{ D_{PL}(|r-r_o|) - D_{PL}(r+r_o) \right\} \quad (7)$$

and the appropriate normalization, we have the following result:

(i)  $r > r_0$

$$D_{\text{SPH}}(r, r_0) = \frac{r_0}{2\pi} K_{\text{SPH}} \mu_{\text{en}}(E_0) E_0 E_1[\mu_0(r-r_0)] +$$

$$+ \frac{r_0}{r} K_{\text{SPH}} \mu_{\text{en}}(E_0) E_0 \left\{ A_1 e^{-B_1 \mu_0 r} \sinh(B_1 \mu_0 r_0) + A_2 e^{-B_2 \mu_0 r} \sinh(B_2 \mu_0 r_0) \right\}$$

(ii)  $r < r_0$

(8)

$$D_{\text{SPH}}(r, r_0) = \frac{r_0}{2r} K_{\text{SPH}} \mu_{\text{en}}(E_0) E_0 E_1[\mu_0(r_0-r)] +$$

$$+ \frac{r_0}{r} K_{\text{SPH}} \mu_{\text{en}}(E_0) E_0 \left\{ A_1 e^{-B_1 \mu_0 r_0} \sinh(B_1 \mu_0 r) + A_2 e^{-B_2 \mu_0 r_0} \sinh(B_2 \mu_0 r) \right\}$$

With  $K_{\text{SPH}}$  in  $\text{sec}^{-1}$ , and the other quantities in the same units as in the plane source problem,  $D_{\text{SPH}}$  is in  $\text{rads sec}^{-1}$ .

#### 4. Comments

The results of this paper are intended chiefly for applications to situations where an analytical representation of the dose distribution is useful. Tables with complete numerical results for the dose distributions from point-isotropic and plane isotropic sources will be published in later reports. Further work is also in progress to obtain not only the spatial distribution of the dose, but also the directional distribution of the radiation giving rise to the dose.

We are indebted to Mr. J. Lamkin and Mrs. I. Reingold for help with the computations.

$E_0$ (Mev)	Al $\mu_0$ ( $\text{cm}^2/\text{g}$ )	Concrete $\mu_0$ ( $\text{cm}^2/\text{g}$ )	Air $\mu_{\text{en}}(E_0)$ ( $\text{cm}^2/\text{g}$ )	$A_1$	$A_2$	$B_1$	$B_2$
10.22	.0228	.0228	.0144	0.00085	0.27904	1.55034	0.99218
6.81	.0253	.0256	.0157	0.00689	0.39173	1.46162	0.99425
3.41	.0333	.0342	.0196	-0.03842	0.63979	1.39280	0.98916
2.04	.0427	.0441	.0232	-0.14505	0.89909	1.30878	0.98127
1.28	.0543	.0562	.0266	-0.35610	1.25634	1.21554	0.97062
0.852	.0663	.0686	.0287	-0.69202	1.73577	1.14244	0.95916
0.511	.0832	.0862	.0297	-1.35130	2.62614	1.08074	0.94685
0.319	.101	.104	.0290	-1.71335	3.23857	1.06037	0.93355
0.213	.117	.121	.0272	-1.61858	3.39072	1.06061	0.92969
0.128	.143	.149	.0240	-0.91086	2.87029	1.07050	0.94280
0.0730	.201	.214	.0246	0.33281	1.33242	1.66004	0.98954
0.0426	.443	.474	.0546	0.30688	0.37299	1.80194	1.05416
0.0341	.745	.793	.100	0.18547	0.18908	1.91352	1.06999

Table 1. Parameters of dose distribution



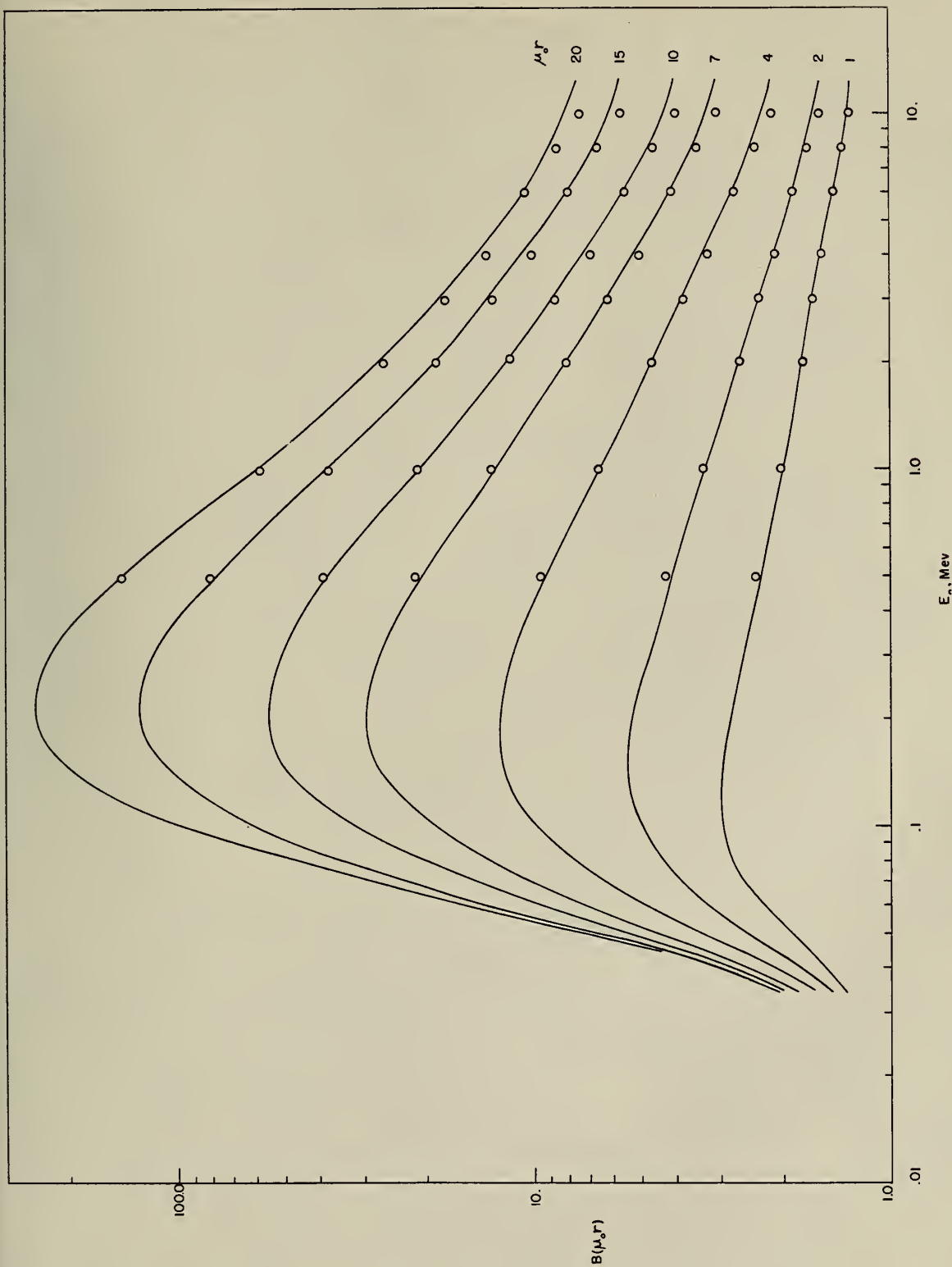


Figure 1. Comparison of the polynomial expansion and "function fitting" methods for calculating  $B(r)$  vs  $E_0$  for different values of  $\mu_0 r$ .





NATIONAL BUREAU OF STANDARDS

A. V. Astin, *Director*

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