PB 151370

NBS

Technical Note 11

PENETRATION OF GAMMA RAYS FROM ISOTROPIC SOURCES THROUGH ALUMINUM AND CONCRETE

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.25) and its Supplement ($0.75), available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

Inquiries regarding the Bureau's reports should be addressed to the Office of Technical Information, National Bureau of Standards, Washington 25, D. C.

NATIONAL BUREAU OF STANDARDS
Technical Note

11

MAY 11, 1959

PENETRATION OF GAMMA RAYS FROM ISOTROPIC SOURCES THROUGH ALUMINUM AND CONCRETE

Martin J. Berger and Lewis V. Spencer

The work described in this Technical Note was sponsored by the Bureau of Yards and Docks, Department of the Navy.

NBS Technical Notes are designed to supplement the Bureau's regular publications program. They provide a means for making available scientific data that are of transient or limited interest. Technical Notes may be listed or referred to in the open literature. They are for sale by the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.

DISTRIBUTED BY

UNITED STATES DEPARTMENT OF COMMERCE

OFFICE OF TECHNICAL SERVICES

WASHINGTON 25, D. C.

Price 50 cents

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.[1/] This program is based on the use of the moment method.[2/]

1/ 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.

2/ 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.

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.[3/,4/] The new calculations differ from this work

---

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

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

---

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

$E_1(z) = \int_z^\infty (e^{-s}/s)ds$ = exponential integral[5/]

$D_{PL}(z)$ = absorbed air dose[6/] at a distance z from the source plane.

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

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

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

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

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

---

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

---

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 μ_o, 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 ($Z_{effective} \sim 13.4$) 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 cm^2/g, are very close to each other.

3. Other Source Geometries

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

[8/] Cf. Reactor Handbook, Vol. I, Chapter 2.5, AECD 3645 (1955).

(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

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

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

$$D_{PT}(r) = \frac{K_{PT}\mu_{en}(E_o)E_o}{4\pi r^2} e^{-\mu_o r} +$$

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

If r is expressed in cm, K_{PT} in 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 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

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

This expression may be compared with results previously obtained by Goldstein and Wilkins.[3/] 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"[9] which we believe to be

[9] Described in the Encyclopedia article mentioned in footnote 2.

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 = radius of disk source

z = distance from source along axis of disk

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

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

Using the general relation

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

and the appropriate source normalization, we obtain the result

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

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

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

and the appropriate normalization, we have the following result:

(i) $r > r_o$

$$D_{SPH}(r,r_o) = \frac{r_o}{2\pi} K_{SPH}\mu_{en}(E_o)E_o \; E_1[\mu_o(r-r_o)] +$$

$$+ \frac{r_o}{r} K_{SPH}\mu_{en}(E_o)E_o \left\{A_1 e^{-B_1\mu_o r}\sinh(B_1\mu_o r_o) + A_2 e^{-B_2\mu_o r}\sinh(B_2\mu_o r_o)\right\}$$

(ii) $r < r_o$ (8)

$$D_{SPH}(r,r_o) = \frac{r_o}{2r} K_{SPH}\mu_{en}(E_o)E_o \; E_1[\mu_o(r_o-r)] +$$

$$+ \frac{r_o}{r} K_{SPH}\mu_{en}(E_o)E_o\left\{A_1 e^{-B_1\mu_o r_o}\sinh(B_1\mu_o r) + A_2 e^{-B_1\mu_o r_o}\sinh(B_2\mu_o r)\right\} .$$

With K_{SPH} in sec^{-1}, and the other quantities in the same units as in the plane source problem, D_{SPH} is in 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_o (Mev)	Al μ_o (cm^2/g)	Concrete μ_o (cm^2/g)	Air $\mu_{en}(E_o)$ (cm^2/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

USCOMM-NBS-DC 53,006

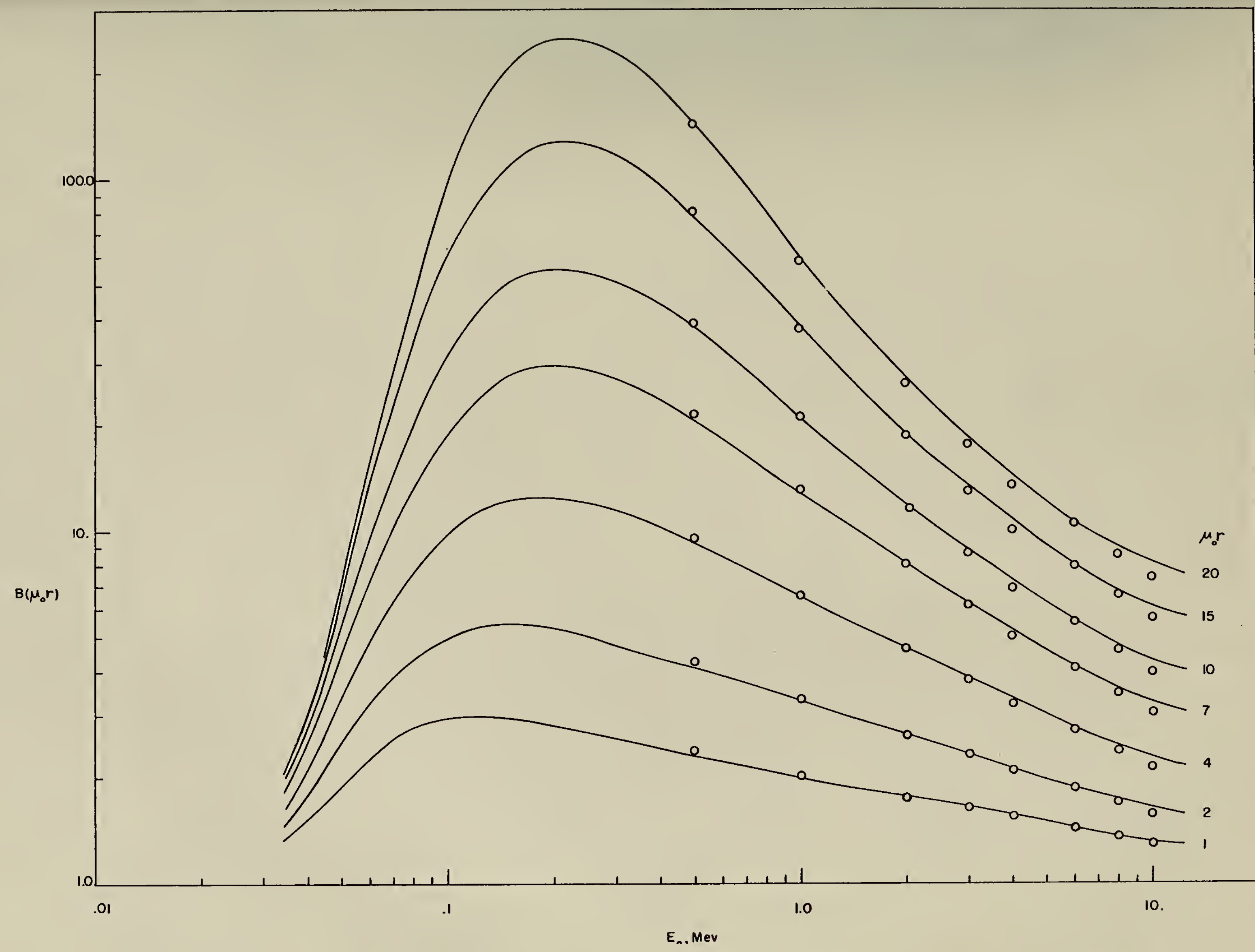

Figure 1. Comparison of the polynomial expansion and "function fitting" methods for calculating B(r) vs E_o for different value of $\mu_o r$.

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its headquarters in Washington, D. C., and its major laboratories in Boulder, Colo., is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside front cover.

WASHINGTON, D. C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Anolog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Ionospheric Communication Systems.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

NBS