UNITED STATES ATOMIC ENERGY COMMISSION

BETA AND GAMMA DOSE RATES FROM TERRESTRIALLY DISTRIBUTED SOURCES

By
Keran O'Brien
Wayne M. Lowder
Leonard R. Solon

October 28, 1957
Health and Safety Laboratory
New York Operations Office
New York, New York

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ABSTRACT

Dose rates in air and at various depths in tissue produced by concentrations of natural isotopes in the ground are calculated for both beta and gamma radiation. Calculated gonadal "screening factors" are within 4% of the experimental values reported by the British Medical Research Council.
This paper presents the results of calculations of dose rate from uranium, thorium, and potassium sources in equilibrium with their decay products distributed uniformly throughout the ground which we have represented as a half space. These dose rates are calculated for various heights in air and at various depths in tissue. An estimate is made of the gamma-ray dose rate delivered to the gonads.

When calculating the dose rate at a point detector in a medium irradiated by a distribution of point sources, it is possible to use what might be termed the "point-source function" approach. We have assumed that the dose rate from a point-source to a point detector is a function of distance alone; that is, it propagates along the radius vector between them. The contributions at the detector were added up by integrating over the point-source distribution.

The principal gamma source energies from the uranium, thorium, and potassium decay series run from 0.2 to 2.6 Mev. As soils and tissue are composed essentially of light elements we have assumed that the principal gamma interaction is Compton scattering, and have used the point-source function for Compton scatterers described by O'Brien, Lowder,
and Solon. For beta radiation we have used the point-source function described by Loevinger. Our "man" is a water cylinder with a 15 cm radius. The effective values of Z and A for a typical soil closely approximate those of aluminum within the range of interest of gamma energies, and we have used coefficients as determined for Al and H2O. Loevinger's beta-ray coefficients were corrected only for the differing densities of air and soil.

The gamma dose rate at the center of a water cylinder can be determined by adding up the dose rate contributed from sources uniformly distributed in the soil. This point was chosen at a height of one meter above the ground. At this distance air absorption and scattering are negligible (see Fig. 1). A calculation at 1 Mev indicates that the radiation shining up through the bottom of the cylinder can be disregarded, which greatly simplifies the necessary computation. The free-air dose rate from an infinite half space unshadowed by any absorbing material is then simply $E/2$, where $E$ is the Mev/g-sec released in the soil. The depth dose rate as a fraction of the free-air dose rate can be expressed as a polynomial of the form

$$\sum_{i=1}^{\infty} A_i \xi_i(t) t^i$$

where $t$ is the cylinder radius in mean free paths corresponding to the source energy,

$$\xi_1(t) = \frac{\pi}{2} \int_0^\infty (\csc \theta)^{i-1} \exp(-t \csc \theta) d\theta$$

and the $A_i$ are numerical coefficients. The form of the above expressions and the computation of the $A_i$ have appeared earlier. The $\xi_1(t)$ were determined by Simpson's rule.
The eccentric points in the cylinder were determined by assuming the cylinder to be made of semi-cylinders; the first having a radius equal to the depth of interest and the second having a radius such that the sum of the areas of the semi-cylindrical cross sections will be equal to $225 \pi \text{ cm}^2$ (see Fig. 2). The procedure of approximating the cylinder by dividing it into semi-cylindrical regions, serves to surround each point at which a calculation is made with the same mass of tissue that would surround it in the actual cylinder. The point most affected by this semi-cylindrical approximation would be the point at zero depth. An exact calculation was carried out by numerical methods for this point using a source energy of 1.5 Mev. This number was higher by 4.2% than the number obtained by the semi-cylindrical approximation.

All gamma-ray calculations were carried out by using the model spectra of Table I. These are representative of the properties of igneous rock and sedimentary sandstone (A), sedimentary limestone (B), and an intermediate type of rock (C). The beta-ray calculations on the other hand were performed separately for each parent element, assigning source energies to six equal intervals from 0.25 to 2.75 Mev. The energy released per gram of soil per second for beta emitters was determined from the maximum beta energy. The mean value for the ratio of the average to the maximum beta energy was determined for a large number of isotopes using data given by Marinelli, Brinckerhoff, and Hine. (6)

We set

$$E_{av} = .38 E_{max}$$

Both beta and gamma-ray dose rates as a function of height above ground were determined, the first by integrating Loevinger's expression. (2)
the second by our procedure, \(^{(1)}\) (see Fig. 1). The variation of the gamma dose rate with height was essentially identical for all three model spectra, and for the beta dose rates both A and C were essentially identical.

Table II was computed from the equations and by the method mentioned above. Table III is the result of weighing Table I with Table II, giving depth-dose curves for the three model gamma-ray spectra.

Reported mutagenic effects of radiation have rendered the gonadal dose a significant quantity in considerations of environmental radiation. The recent report of the British Medical Research Council\(^{(2)}\) gives the ratio of the testicular and ovarian dose rates to the free-air dose rate based on measurements with a water-filled phantom. The mean value of these "screening factors" are 0.70 and 0.56 respectively. Assuming a depth of 1 cm for the testes and 7 cm for the ovaries,\(^{(9)}\) the data of Table III gives us 0.68 and 0.58; within 4% of the British results.

The free-air dose rates in Table IV were determined by \(E/2\), as above. The skin and gonadal doses are the free-air doses multiplied by factors from Table III; 0.70 for skin dose and the screening factors for the gonadal dose.

The free-air dose rates in Table V come by way of Loevinger's expression, as above. Because a human body is infinitely deep to beta rays of the energies met with from natural sources, the skin doses in Table V are simply \(1/2\) the free-air doses. Table VI results from comparing the free-air dose rates in Tables IV and V.
No attempt was made to compute doses due to "natural fallout" from the gaseous components of the uranium and thorium decay chains present in the air. The distribution of these would no doubt affect beta and gamma doses as measured above ground, but it would depend too sensitively on topography and local meteorology. This contribution is not expected to be important. \(^{(10)}\)

Our figures in Table VI are lower than the corresponding values given by Hess, et al.; \(^{(10)}\) but this may be due to a much higher concentration of potassium in the rock and soil types measured by them than in our models.
BIBLIOGRAPHY


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5. B. Hultqvist; Kgl. Svenska Vetenskapsakad. Handl. (k) 6 No. 3 (1956).


7. R. Loewinger; Physics in Medicine and Biology 1, 330 (1947).

8. Medical Research Council; The Hazards to Man of Nuclear and Allied Radiations, Cmd. 9780 (1956).


TABLE I

Free-air gamma-ray dose spectra

Fractional dose-rate assigned to each source-energy value for three types of stone.

<table>
<thead>
<tr>
<th>E (Mev)</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>.162</td>
<td>.207</td>
<td>.170</td>
</tr>
<tr>
<td>0.75</td>
<td>.217</td>
<td>.175</td>
<td>.168</td>
</tr>
<tr>
<td>1.5</td>
<td>.499</td>
<td>.516</td>
<td>.544</td>
</tr>
<tr>
<td>2.25</td>
<td>.122</td>
<td>.102</td>
<td>.118</td>
</tr>
<tr>
<td>E (Mev)</td>
<td>0</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>0.375</td>
<td>.667</td>
<td>.577</td>
<td>.527</td>
</tr>
<tr>
<td>0.75</td>
<td>.681</td>
<td>.602</td>
<td>.554</td>
</tr>
<tr>
<td>1.5</td>
<td>.708</td>
<td>.654</td>
<td>.607</td>
</tr>
<tr>
<td>2.25</td>
<td>.735</td>
<td>.705</td>
<td>.660</td>
</tr>
</tbody>
</table>
β-8

A.E.C.

β & δ Dose Rates from Terrestrial Distr. Sources

H W Vandeviere

H W VANDEVEIRE

NUCLEAR EGR

Recallable in 14 X Days
<table>
<thead>
<tr>
<th>Model</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>.699</td>
<td>.636</td>
<td>.589</td>
<td>.552</td>
<td>.527</td>
<td>.516</td>
</tr>
<tr>
<td>B</td>
<td>.698</td>
<td>.634</td>
<td>.587</td>
<td>.549</td>
<td>.524</td>
<td>.513</td>
</tr>
<tr>
<td>C</td>
<td>.700</td>
<td>.638</td>
<td>.591</td>
<td>.554</td>
<td>.529</td>
<td>.518</td>
</tr>
</tbody>
</table>

A - Igneous rock and sedimentary sandstone
B - Sedimentary limestone, and
C - Intermediate stone
Gamma dose-rate per microgram of parent element per gram of soil at one meter from ground.

<table>
<thead>
<tr>
<th>Element</th>
<th>Free Air</th>
<th>Skin</th>
<th>Testicular</th>
<th>Ovarian</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μrad/hr</td>
<td>mrad/yr</td>
<td>mrad/yr</td>
<td>mrad/yr</td>
</tr>
<tr>
<td>U</td>
<td>.660</td>
<td>5.79</td>
<td>4.04</td>
<td>3.93</td>
</tr>
<tr>
<td>Th</td>
<td>.319</td>
<td>2.79</td>
<td>1.95</td>
<td>1.90</td>
</tr>
<tr>
<td>K (x 10^3)</td>
<td>.152</td>
<td>1.33</td>
<td>.929</td>
<td>.904</td>
</tr>
</tbody>
</table>
### TABLE V

Beta dose-rates per microgram of parent element per gram of soil.

<table>
<thead>
<tr>
<th>Element</th>
<th>Free-air - mrad/yr</th>
<th></th>
<th>Skin - mrad/yr</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 height</td>
<td>1 meter height</td>
<td>1.5 meter height</td>
<td>1 meter height</td>
</tr>
<tr>
<td>U</td>
<td>5.75</td>
<td>2.06</td>
<td>1.43</td>
<td>1.03</td>
</tr>
<tr>
<td>Th</td>
<td>1.49</td>
<td>.481</td>
<td>.316</td>
<td>.241</td>
</tr>
<tr>
<td>K (x 10³)</td>
<td>3.43</td>
<td>.634</td>
<td>.0453</td>
<td>.171</td>
</tr>
</tbody>
</table>
TABLE VI

Percent of total dose-rate due to beta rays for three models.

<table>
<thead>
<tr>
<th>Model</th>
<th>0 meters</th>
<th>1 meter</th>
<th>1.5 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>58.6</td>
<td>24.9</td>
<td>14.8</td>
</tr>
<tr>
<td>B</td>
<td>53.6</td>
<td>25.7</td>
<td>18.0</td>
</tr>
<tr>
<td>C</td>
<td>57.8</td>
<td>25.1</td>
<td>15.4</td>
</tr>
</tbody>
</table>

A - Igneous rock and sedimentary sandstone
B - Sedimentary limestone, and
C - Intermediate stone
FIGURE 1: VARIATION OF TERRESTRIAL DOSE-RATE WITH ALTITUDE AS CALCULATED FOR
A. Igneous Rock and Sedimentary Sandstone
B. Sedimentary Limestone, and
C. Intermediate stone
The beta-ray dose rates are relative to a gamma-ray surface dose rate of unity.
FIGURE 2: GEOMETRY USED FOR DEPTH-DOSE CALCULATIONS:

A cross section of the cylinder