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RADIOACTIVE POLLUTION OF THE EARTH'S ATMOSPHERE

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RADIOACTIVE POLLUTION OF THE EARTH'S ATMOSPHERE

F. Reines

INTRODUCTION:

Estimates are given for the number of atomic bombs which will give rise to various radiation levels in R units at the earth's surface. These radiation levels can be compared with the lethal dose of $\sim$500 R to estimate their lethal effects. Since local atmospheric conditions would very likely cause considerable fluctuation in the density of fission products and hence of the radiation levels, all calculations are applicable only in the statistical sense. More specific answers can only be obtained by meteorological investigations on a vast scale, directed towards the detailed prediction of air mass motion over the surface of the earth.[1] The estimates made here assume uniform distributions of activity per gram of air between various levels of the atmosphere and are valid only after sufficient time has elapsed to allow this condition to be reached. The length of time required will clearly depend on the distribution of explosions in space and time as well as the condition of the atmosphere during and subsequent to the explosions. No attempt is made in this preliminary report to calculate the detailed effects of a spread in firing time but it is probably true that a spread in firing time of one week would have only a small effect ($\sim$5%) on the resultant activity at plus one month from the average starting time.

CALCULATIONS:

The total gamma ray energy emitted from the fission products[2] from +1 hour to ∞ is given by[3].

(1) The interesting question of mixing--or rather lack of it--between the northern and southern hemispheres should perhaps be considered by a meteorologist. Since the present calculation is probably only good to a factor of 10, the factor of 2 involved in the hemisphere mixing question does not significantly alter the estimates for one hemisphere.

(2) Induced activities in naturally present or intentionally placed surrounding media are neglected as are β rays and the effects of P_u. These neglections probably do not alter the results by a factor of two.

(3) LAMS-507.

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(1) $S = \frac{nf}{v} \times 6 \times 10^5$ ev/cm^3 where n = number of bombs

v = volume through which fission products are spread (cm^3)

f = total number of fissions per bomb

For a 20% efficient explosion of a Nagasaki-type bomb

$f = 4 \times 10^{24}$ fissions/bomb

The total radiation in R units at point O (See Fig. 1a), R_o, is given by

(2) $R_o = 5 \times 10^{-16}\, I_o$ (Chicago Handbook Chapter XII, Sect. A-2)

where I_o is given by

(3) $$I_o = \int_v \frac{S\, e^{-\frac{r}{\lambda}}\, dv}{4\pi r^2}$$

and $\lambda \cong 3 \times 10^4$ cm at sea level.

The time dependence of R is given by

(4) $$\frac{dR}{dt} = \frac{C}{t^{1.2}} \quad \text{or} \quad R_o = \int_{1\,hr}^{\infty} \frac{Cdt}{t^{1.2}} = 5C$$

Because the mean free path in air of the γ's given off by the fission products have a range of $\sim 3 \times 10^4$ cm, a distance short compared with those in which effects due to the earth's curvature enter, the replacement of spherical by plane geometry is essentially exact and will be employed because of the simplifications it introduces into the calculations. The γ source strength is calculated by considering the actual spherical geometry. We will now calculate I_o under these assumptions: I for a somewhat fictitious but simple case, then II for a more realistic but more complex case.

I. CONSTANT AIR DENSITY; UNIFORM SOURCE DISTRIBUTION per cm^3

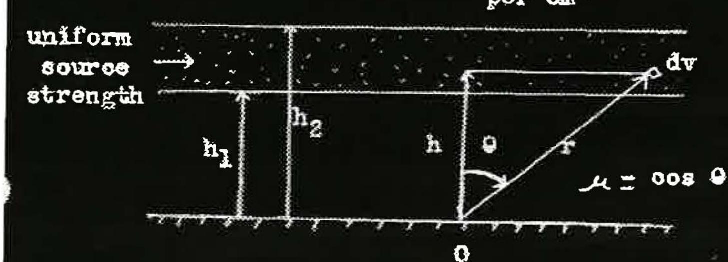

FIG. 1a

FIG. 1b

For S independent of r, and $\lambda =$ constant (3) becomes

$$I_o = S \int_v \frac{e^{-\frac{r}{\lambda}}}{4\pi r^2} \, dv = \frac{S}{2} \int_{\mu=o}^{1} \int_{r_1=\frac{h_1}{\mu}}^{r_2=h_2/\mu} e^{-\frac{r}{\lambda}} \, dr \, d\mu$$

$$(5) \quad I_o = \frac{S\lambda}{2} \left[\frac{h_1}{\lambda} \, F\left(\frac{h_1}{\lambda}\right) - \frac{h_2}{\lambda} \, F\left(\frac{h_2}{\lambda}\right) \right]$$

For plot of $\frac{h}{\lambda} \, F\left(\frac{h}{\lambda}\right) = G\left(\frac{h}{\lambda}\right)$ see Fig. 2.

To calculate S, we take the activity uniformly distributed over spherical shell of radius R and thickness h_2-h_1.

$$(6) \quad S = \frac{nf \times 6 \times 10^5}{4\pi R_e^2 (h_2-h_1)}$$

From this, inserting $f = 4 \times 10^{24}$, $R_e = 6.38 \times 10^8$ cm, $\lambda = 3 \times 10^4$, and using (2) we get

$$(7) \quad n = \frac{(h_2-h_1)R_o}{3.5\left[G\left(\frac{h_1}{\lambda}\right) - G\left(\frac{h_2}{\lambda}\right)\right]}$$

Table I gives a summary of values of n corresponding on the above assumptions to given total dosages R_o and assumed values of h_1 and h_2. Since the atmosphere is not of constant density but has a density which drops off exponentially, only assumptions (1) and (2) give results in reasonable accord with those following from actual density variation. Assumptions (3), (4), (5), (6) are calculated for constant density to show by comparison with TABLE II the effect of varying air density. As might be expected, it is considerable.

TABLE I

Summary of total Dosages in R units (Constant Air Density)

R_o	(1) h_2 =1000 ft h_1 =0	(2) h_2 =3000 h_1 =0	(3) h_2=5000 h_1=0	(4) h_2=20,000 h_1=1,000	(5) h_2=15,000 h_1=5,000	(6) h_2=20,000 h_1=10,000
0.1	10^3	2.5×10^3	2×10^4	10^5	8×10^6	2×10^9
1	10^4	2.5×10^4	2×10^5	10^6	8×10^7	2×10^{10}
10	10^5	2.5×10^5	2×10^6	10^7	8×10^8	2×10^{11}
100	10^6	2.5×10^6	2×10^7	10^8	8×10^9	2×10^{12}
1000	10^7	2.5×10^7	2×10^8	10^9	8×10^{10}	2×10^{13}

II. VARIABLE AIR DENSITY: UNIFORM SOURCE DISTRIBUTION PER GRAM OF AIR:

The density of the atmosphere is reasonably well represented by

(8) $\rho = \rho_o e^{-\alpha h}$ where: h is the altitude above sea level (cm)

ρ_o is the density at sea level

ρ is the density at height h

$\alpha = 1.252 \times 10^{-6}/\text{cm}$

The density ratio $\frac{\rho}{\rho_o}$ can be represented by a straight line to within an accuracy of 4% in the range 0-20,000 ft., ($0-61\times10^4$ cm)

(9) $\frac{\rho}{\rho_o} = a - bh$

$a = 0.960$

$b = 8.26\times10^{-7}$

In consequence of (8)

(10) $S(h) = S_o\, e^{-\alpha h}$

and

(11) $\frac{1}{\lambda} = \frac{1}{\lambda_o} e^{-\alpha h} \simeq \frac{1}{\lambda_o}(0.960 - 8.26\times10^{-7}h)$, $\lambda_o \cong 3\times10^4$ cm.

Inserting (10) and (11) into (3) and writing out limits

(12) $$I_o = \frac{S_o}{2}\int_{\mu=0}^{1}\int_{r_1=\frac{h_1}{\mu}}^{r_2=\frac{h_2}{\mu}} e^{-(\alpha\mu + \frac{a}{\lambda_o})r + b\frac{\mu r^2}{\lambda_o}}\, dr\, d\mu$$

S_o is determined by the requirement that $\int_V S(h)dv = A = nf\times6\times10^5$ = total activity.

If the activity is distributed in a spherical shell extending from radius $R_{earth} + h_1$ to $R_{earth} + h_2$ where $h_1 < h_2 <<< R_{earth}$

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$$(13)\quad S_o = \frac{A}{4\pi R_{earth}^{2}\ \frac{e^{-\alpha h_1} - e^{-\alpha h_2}}{\alpha}}$$

A transformation of variables $r = (h_2 - h_1)S + h_1$ reduces (12) to one integration. TABLE II summarizes the results.

TABLE II

Summary of Total Dosages in R Units (Exponentially Varying Air Density)

R_o	(1) h_2 = 1,000 ft h_1 = 0 ft	(2) 3,000 0	(3) 5,000 0	(4) 20,000 1,000	(5) 15,000 5,000	(6) 20,000 10,000
0.1	10^3	2.5×10^3	3.5×10^3	6×10^4	2×10^6	3×10^7
1	10^4	2.5×10^4	3.5×10^4	6×10^5	2×10^7	3×10^8
10	10^5	2.5×10^5	3.5×10^5	6×10^6	2×10^8	3×10^9
100	10^6	2.5×10^6	3.5×10^6	6×10^7	2×10^9	3×10^{10}
1000	10^7	2.5×10^7	3.5×10^7	6×10^8	2×10^{10}	3×10^{11}

In the light of past experience, assumptions (5) and (6) are reasonably realistic. The number of bombs which produce a lethal effect over the entire world is on this basis so large that it amounts to destroying the entire world population by allocating ~1 bomb to each person!

THE BEHAVIOR OF ACTIVITY AT PT. O:

An item of interest is the number of atomic bombs which will give the legal daily tolerance dose of 0.1 R/day after one month. From (4) we find that a total activity of $R_o = 56$ R units will give 0.1 R/day at + 30 days. Translating this total dose into numbers of bombs on the various assumptions for h_1, h_2 in TABLE II we find

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TABLE III

Number of bombs, n, which will give 0.1 R/day after 30 days:

	h_2=1000 h_1=0	3000 0	5000 0	20,000 1,000	15,000 5,000	20,000 10,000
n	5×10^5	1.5×10^6	2×10^7	3×10^7	10^9	1.5×10^{10}

Another item of interest is the number of bombs which will give a daily dose at + 30 days equal to that provided by cosmic rays.

The cosmic ray background at sea level has been measured[4] to be 1.66 ions/cm^3 per sec. Since

$$1 \text{ R/day} = 2\times10^9 \text{ ions/cm}^3 \text{ per day},$$

the cosmic ray background

$$= 7.2 \times 10^{-5} \text{ R/day}.$$

The value of n required to equal cosmic ray background[5] at + 30 days is listed in TABLE IV.

TABLE IV

Number of bombs n which will give ionization equal to CR background after 30 days

h_2 h_1	1000 0	3000 0	5000 0	20,000 1,000	15,000 5,000	20,000 10,000
n	4×10^2	10^3	1.5×10^4	2.5×10^5	10^6	10^7

UNIFORM SURFACE DISTRIBUTION:

The simplest manner in which to calculate the number of atomic bombs required on this assumption to cause given radiation levels is to perform a limiting process on Equation (3).

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(4) Clay and Jongen Physica 4:245-255, 1937.

(5) Incidentally, it is not clear that even such a low radiation dosage as that represented by cosmic rays has negligible effect on humans. The fact that cosmic rays affect the rate of mutation of drosophila suggests wider possible biological implications.

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The situation $h_1=h_2=0$ represents a uniform deposition of activity on the surface, i.e.

$$I_{o\ \text{surface}} = \lim_{\substack{h_2 \to h_1+\epsilon \\ z \to 0}} I_o = \lim_{z \to 0} \frac{SE}{z}$$

But by (1)

$$\lim_{z \to 0} \frac{SE}{z} = \frac{nf \times 6 \times 10^5}{8\pi R^2_{earth}} \quad \text{and hence}$$

$$(8) \quad n = 0.9 \times 10^4\, R_{os}$$

TABLE IV

Number of bombs to give assumed total doses for uniform surface distribution of activity

R_{os}	n	
0.1	$10^3 x 0.9$	compare with
1	$10^4 x 0.9$	TABLES I, II
10	$10^5 x 0.9$	entry $h_1=1000$ ft ($= 3\times10^4$ cm) ≈ λ
100	$10^6 x 0.9$	
1000	$10^7 x 0.9$	$h_1=0$

DISCUSSION

The above calculation assumes a uniform distribution of fission products per gram of air. Such a uniform distribution takes time to be established. During this time the activity decays somewhat indicating that the figures in the tables for the total dose are somewhat too high on the average. In addition the area affected by the direct radiation from the bomb in the act of explosion is far from negligible, since it affects ~ 2 miles^2 per bomb. Further, it is clear that until the mixing becomes uniform, as assumed here, there will undoubtedly be regions of relatively large concentrations causing departures from the figures cited in the tables. These departures depend on the initial disposition of explosions: a more homogeneous disposition would tend to give figures like those in the tables. Since as time goes on the mixing becomes more complete, the figures for the numbers of bombs required to give 0.1 R/day at a month are representative, and more or less independently of the initial distribution.

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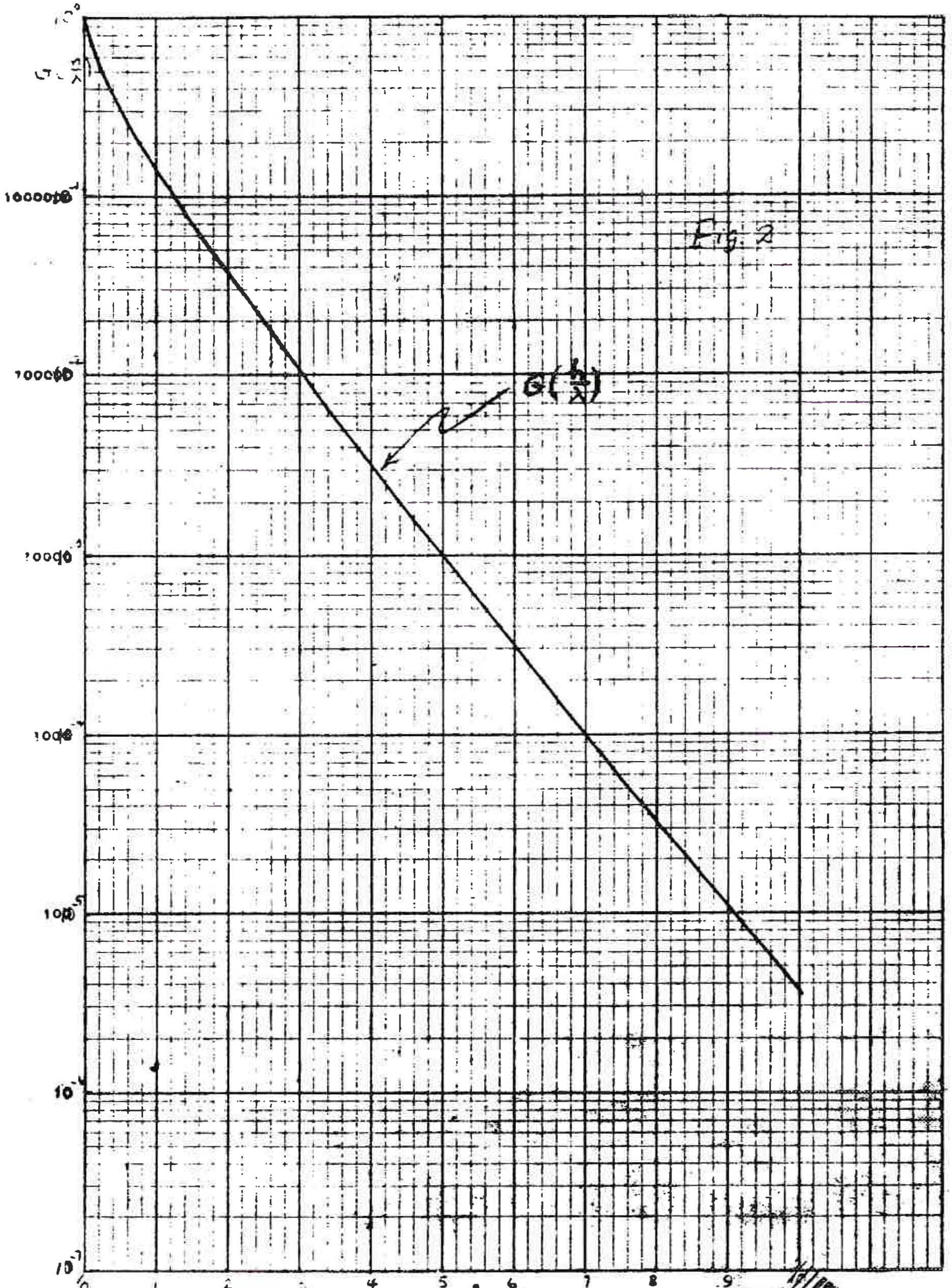

Fig. 2

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