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Lawrence Radiation Laboratory

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A GRAPHICAL METHOD FOR CALCULATING THE DOSE IN MAN FROM INDIVIDUAL RADIONUCLIDES IN FALLOUT

C. Ann Burton

June 3, 1966

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A GRAPHICAL METHOD FOR CALCULATING THE DOSE IN MAN FROM INDIVIDUAL RADIONUCLIDES IN FALLOUT

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ABSTRACT

The fallout deposition required to deliver a specific integrated 30-yr dose to any tissue in man, for any and all radionuclides in a single event, is presented in graphical as well as analytical form. The model used is consistent with the data that are available to this problem at the present time. A table of effective tissue half-lives for given radiological and biological half-lives is given for use with the graphs. Sample calculations are also included.

INTRODUCTION

When a thermonuclear device is exploded underground, there are three sources of radionuclide production; (1) fission products from the fission yield of the device, (2) radionuclides induced in the materials of the device and (3) radionuclides induced within the ground materials (i.e., granite) surrounding the device. The last two result from neutrons emitted by the device, particularly by the thermonuclear reaction. Thus, in such an event, radionuclides of elements from all groups in the periodic table can be produced.

In order to determine the possible biological implications of projects such as the construction of a sea level canal using nuclear devices, it is essential to be able to predict the ultimate burden in man and the resultant dosage to man from any and all of these radionuclides.

Previous mathematical models[1,2] relating fallout deposition to the integrated dose in man have treated the problem in great detail. The data required to compute the necessary parameters for most of the wide variety of radionuclides that would be produced are not available. When data are known, the accuracy is usually not sufficient to warrant the use of a complex model.

The purpose of this report is to present a set of graphs and a table that can be used to easily calculate the dose that would be delivered to man, or any organ of man, from any radionuclide produced in the detonation of a nuclear device once its deposition per unit area of terrain is determined.[3] Conversely, the graphs and table can be used to determine the limiting deposition that would lead to a particular dose to an organ of man. The model used to derive these solutions is consistent with the nature of the data that are available to this problem at the present time. That is, the model has been so developed that, by using existing data, one can at least make worst case assumptions and arrive at a dosage estimate that is conservative from the standpoint of public health and safety. This report will only present the model and some sample solutions. A subsequent report from this laboratory will present a tabulation of the input data and, where necessary, the worst case assumptions for the various radionuclides.

DERIVATION OF THE GENERAL EQUATION

If we let Q be the fraction of the energy in MeV absorbed by the tissue in question per disintegration of radionuclide i, then the dose to that tissue in time dt can be written[4]

$$\frac{dD(t)}{dt} = 1.6 \times 10^{-8} \lambda_R \; Q \; n_B^*(t). \tag{1}$$

where

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[1] International Commission on Radiological Protection. ICRP Publication 2, "Report of Committee II on Permissible Dose for Internal Radiation, 1959." New York, Pergamon Press, 1960.

[2] Stanford Research Institute, "Models for Estimating the Absorbed Dose from Assimilation of Radionuclides in Body Organs of Humans," OCD-OS-62-135, 1963.

[3] The equations that follow will assume that the radionuclide decays to a stable daughter. Radioactive chains can be approximated by using appropriate "average" values throughout.

[4] A list of symbols precedes Appendix A.

$D \equiv$ dose in rads

$\lambda_R \equiv$ radioactive decay constant of i in sec^{-1}

$n_B^* \equiv$ number of nuclei of i per gram of tissue at time t.[5]

If we assume first order kinetics, then $n_B^*(t)$ satisfies the equation

$$\frac{dn_B^*}{dt} = U^*(t) - \lambda_E n_B^*(t) \tag{2}$$

where

$U^*(t) \equiv$ uptake rate in nuclei per gram tissue per sec

$\lambda_E \equiv$ effective decay constant in tissue in sec^{-1}

The latter is the sum of the radioactive decay constant and the biological turnover rate. If the uptake rate depends on time only through the decay of i in the food itself, that is,

$$U^*(t) = U_0^* e^{-\lambda_P t} \tag{3}$$

where

$\lambda_P \equiv$ effective decay rate of i in food in sec^{-1}

then, since $n_B^*(0) = 0$, Eq. 2 has the solution (see Appendix A)

$$n_B^*(t) = \frac{U_0^*}{\lambda_E - \lambda_P}\left[e^{-\lambda_P t} - e^{-\lambda_E t}\right] . \tag{4}$$

Substituting Eq. 4 in Eq. 1, we have

$$\frac{dD}{dt} = \frac{1.6 \times 10^{-8} \lambda_R \; Q \; U_0^*}{\left(\lambda_E - \lambda_P\right)}\left[e^{-\lambda_P t} - e^{-\lambda_E t}\right] . \tag{5}$$

To calculate the dose due to i after 30 yr, we integrate Eq. 5 from t = 0 to t = 30 yr getting

[5]An asterisk following a symbol denotes that the symbol applies to the radionuclide.

$$D_{30} = \frac{1.6 \times 10^{-8} \lambda_R \; Q \; U_0^*}{\left(\lambda_E - \lambda_P\right)} \left[\frac{1}{\lambda_P}\left(1 - e^{-30\lambda_P}\right) - \frac{1}{\lambda_E}\left(1 - e^{-30\lambda_E}\right)\right] . \tag{6}$$

Converting the decay constants to their respective half-lives ($T = 0.693/\lambda$), we have

$$D_{30} = \frac{2.31 \times 10^{-8} \; Q \; T_E \; T_P \; U_0^*}{T_R\left(T_P - T_E\right)} \left[T_P\left(1 - e^{-20.8/T_P}\right) - T_E\left(1 - e^{-20.8/T_E}\right)\right] . \tag{7}$$

We must now evaluate U_0^* in terms of the fallout deposition. Two cases will be considered: fallout on forage and fallout mixed with soil.

FALLOUT ON FORAGE

The primary route for fallout on forage to man is through cows' milk. However, a simple modification of the parameters in the derivation that follows will make it valid for any food chain, e.g., lettuce, where the fallout is deposited directly on the food in question.

If $F \mu Ci/m^2$ of i are deposited, this corresponds to N^* nuclei/m^2 such that

$$N^* = 3.7 \times 10^4 \frac{F}{\lambda_R} = 16.82 \times 10^{11} F \; T_R \tag{8}$$

where λ_R is in sec^{-1} and T_R is in yr. If a cow forages (UAF)m^2/day, then its consumption of i is, in nuclei/day

$$B_0^*(\text{cow}) = (\text{UAF})N^* . \tag{9}$$

Of this, a fraction f_M appears in each liter of milk. If man consumes b liters/day of milk, then his consumption of i is, in nuclei/day

$$B_0^*(\text{man}) = (\text{UAF})N^* \; b \; f_M . \tag{10}$$

A fraction f_B reaches the tissue in question. Thus, the uptake rate in nuclei per gram of tissue of mass m per year is

$$U_0^* = 365(\text{UAF})N^* \; b \; f_M \; f_B/m . \tag{11}$$

Substituting Eq. 8 in Eq. 11, we have

$$U_0^* = 6.14 \times 10^{14} F\, T_R (UAF)\, b\, f_M\, f_B/m\,. \tag{12}$$

Substituting Eq. 12 in Eq. 7 and solving for F, we have

$$F = \frac{7.04 \times 10^{-8}\, D_{30}\, (T_P - T_E)}{(UAF)\, b\, Q\, f\, T_E\, T_P} \cdot \frac{1}{\left[T_P\left(1 - e^{-20.8/T_P}\right) - T_E\left(1 - e^{-20.8/T_E}\right)\right]} \tag{13}$$

where

$$f \equiv f_M\, f_B/m\,.$$

Note that the half-life for particles on forage is generally taken to be 14 days.[6] Thus, T_P is always small with respect to 30 yr and Eq. 13 reduces to

$$F = \frac{7.04 \times 10^{-8}\, D_{30}}{(UAF)\, b\, Q\, f\, T_P\, T_E} \quad \frac{\left(1 - T_P/T_E\right)}{\left(1 - T_P/T_E - e^{-20.8/T_E}\right)} \tag{13'}$$

If T_E is also small, then Eq. 13 further reduces to

$$F = \frac{7.04 \times 10^{-8}\, D_{30}}{(UAF)\, b\, Q\, f\, T_P\, T_E}\,. \tag{14}$$

Equation 13' is plotted as a function of $1/T_E$ in Figs. 1 and 2 for several values of f. The constants have been evaluated for the cow-milk-man chain as follows:

$$(UAF) = 45\ m^2/day$$

$$b = 1\ liters/day$$

The parameters have been chosen as

$$Q = 1\ MeV$$

$$D_{30} = 1\ rad.$$

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[6] S. E. Thompson, "Effective Half-Life of Fallout Radionuclides on Plants With Special Emphasis on Iodine-131," UCRL-12388, January 29, 1965.

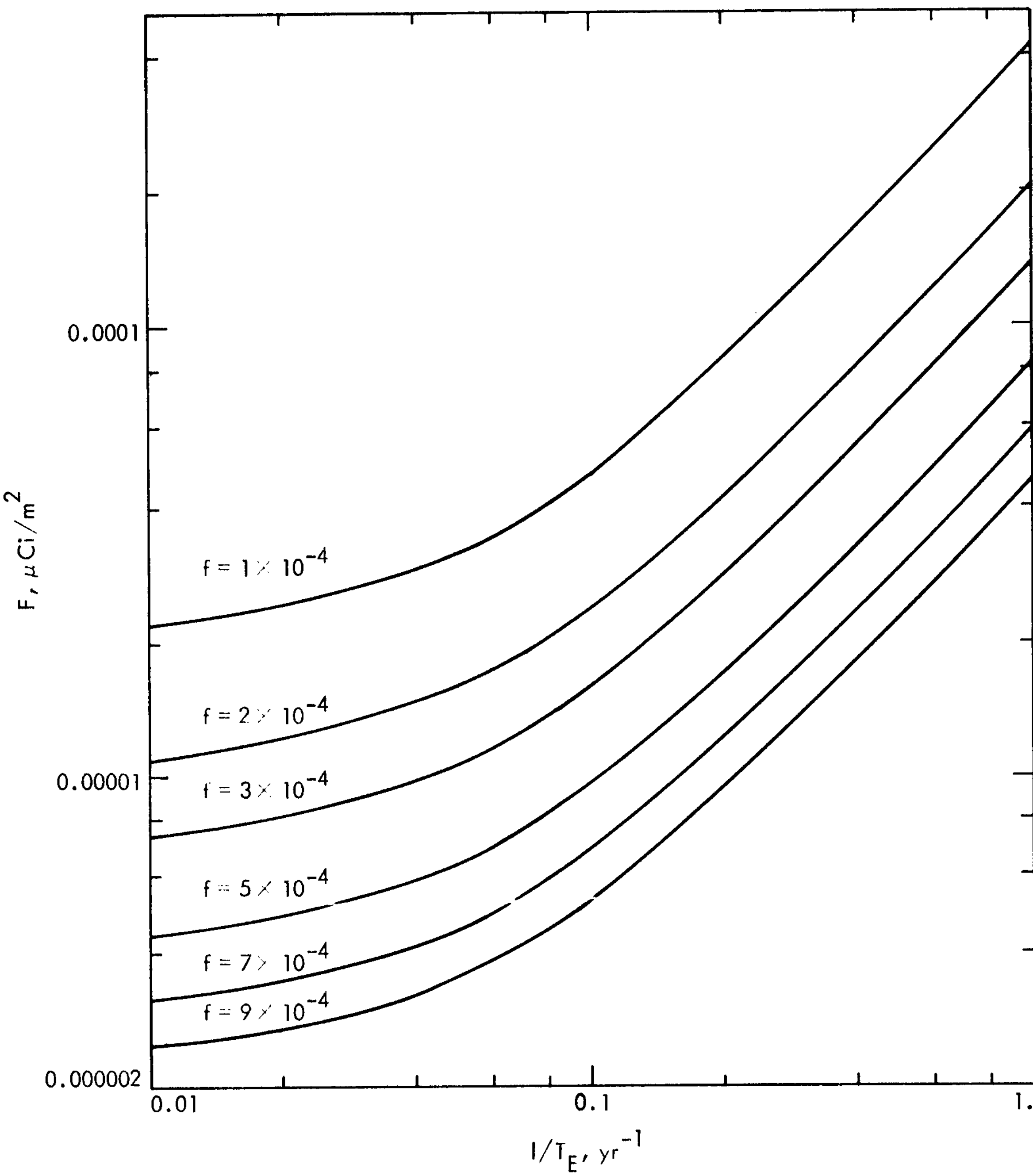

Fig. 1. Deposition required to deliver 1 rad via milk to tissue at Q = 1 MeV for several values of f, with $T_E > 1.0$ yr.

Since T_P rapidly approaches 14 days with increasing T_R, Figs. 1 and 2 are plotted with T_P = 14 days and a correction factor is included for short T_R. The effective half-life in tissue depends on T_R and the biological half-life, T_B. Thus,

$$T_E = \frac{T_R\ T_B}{T_R + T_B} \quad . \tag{15}$$

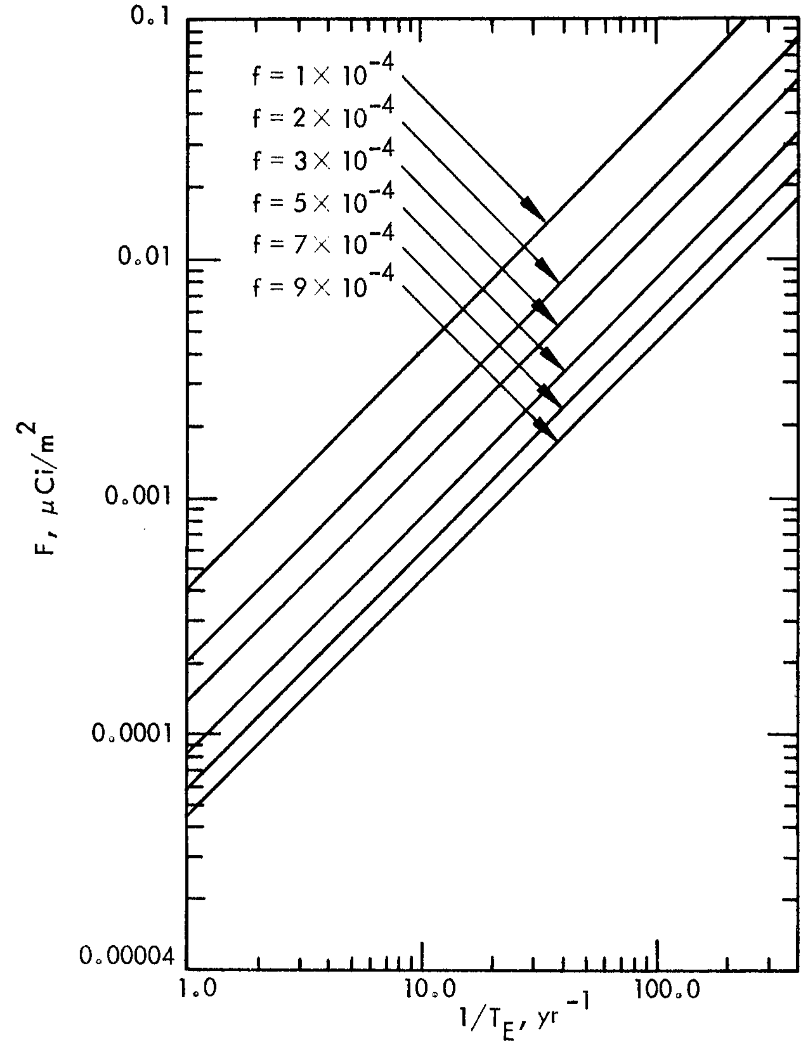

Fig. 2. Deposition required to deliver 1 rad via milk to tissue at Q = 1 MeV for several values of f, with $T_E < 1.0$ yr. Note: If $T_R < 4$ months, multiply F by the correction to T_P listed below:

T_R (days)	1	2	3	4	5	6	7	8
Correction	14.84	7.93	5.62	4.45	3.76	3.30	2.97	2.73
T_R (days)	9	10	15	20	30	60	120	
Correction	2.53	2.39	1.93	1.70	1.46	1.23	1.11	

Appendix C is a table of $1/T_E$ for various values of T_R and T_B. A sample calculation is included in Appendix D.

FALLOUT IN SOIL

When the fallout is mixed with soil by plowing, for example, the specific activity is much lower. We will assume that the specific activity of the plants equilibrates with that of the soil. The uptake rate can be written in terms of the biological half-life. For the stable element dn_B/dt is zero. Thus we can solve Eq. 2 for U.

$$U = \frac{0.693}{T_B} n_B \tag{16}$$

Since the uptake rate is proportional to the number of nuclei present in the soil, (actually those in the biologically exchangeable pool[7]), we can write

$$U_0^* = \frac{U}{n_S} n_S^* \tag{17}$$

where

$n_S \equiv$ number of stable nuclei per g of soil

$n_S^* \equiv$ number of radionuclei per g of soil.

The fallout nuclei, N^*, have been mixed with ρd g/m^2 of soil where

$\rho \equiv$ density of soil in g/m^3

$d \equiv$ depth of plow layer in m.

Thus, using Eq. 8, and assuming that N^* is sufficiently small so that ρ is unchanged, we have

$$n_S^*(0) = \frac{N^*(0)}{\rho d} = \frac{16.82 \times 10^{11}\ F\ T_R}{\rho d} . \tag{18}$$

Substituting Eq. 18 in Eq. 17, and replacing the numbers of nuclei by the corresponding concentrations, the uptake for i is

$$U_0^* = \frac{11.66 \times 10^{11}\ F\ T_R\ C_B}{\rho d\, C_S\ T_B} . \tag{19}$$

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[7] Y. C. Ng and S. E. Thompson, "Applications of the Biological Exchangeable Pool to the Analyses of Environmental Contamination by Radionuclides." To be published.

where

$C_B \equiv$ concentration of stable nuclide in tissue

$C_S \equiv$ concentration of stable nuclide in soil.

Substituting Eq. 19 in Eq. 7 with T_S, the effective half-life in soil, replacing T_P and solving for F, we have

$$F = \frac{3.71 \times 10^{-5} D_{30} \rho d C_S T_B (T_S - T_E)}{Q C_B T_E T_S \left[T_S \left(1 - e^{-20.8/T_S}\right) - T_E \left(1 - e^{-20.8/T_E}\right) \right]} . \tag{20}$$

If the only mode of decay in the soil is radioactive decay, then $T_S = T_R$. Equation 20 becomes

$$F = \frac{3.71 \times 10^{-5} D_{30} \rho d C_S}{Q C_B} \cdot \frac{1}{\left[T_R \left(1 - e^{-20.8/T_R}\right) - T_E \left(1 - e^{-20.8/T_E}\right) \right]} . \tag{21}$$

Since a growing season must intervene between the deposition and consumption by man, short-lived radioisotopes will not enter tissue via the soil-root system. In most cases, then, T_B will be small with respect to T_R and Eq. 21 reduces to

$$F = \frac{3.71 \times 10^{-5} D_{30} \rho d C_S}{Q C_B T_R} \cdot \frac{1}{\left(1 - e^{-20.8/T_R}\right)} . \tag{22}$$

Equation 22 is plotted vs T_R for various values of Q in Fig. 3. C_B is set equal to C_S for convenience. Appropriate values must be obtained from the literature.[8] The constants are evaluated for typical soils with

$\rho = 2.0 \times 10^6 \text{ g/m}^3$

$d = 0.2 \text{ m}$

The parameter D_{30} has been set equal to 1 rad. An alternate derivation of Eq. 22 is given in Appendix B and a sample calculation is given in Appendix D.

[8] Y. C. Ng and S. E. Thompson, "Applications of the Biological Exchangeable Pool to the Analyses of Environmental Contamination by Radionuclides." To be published.

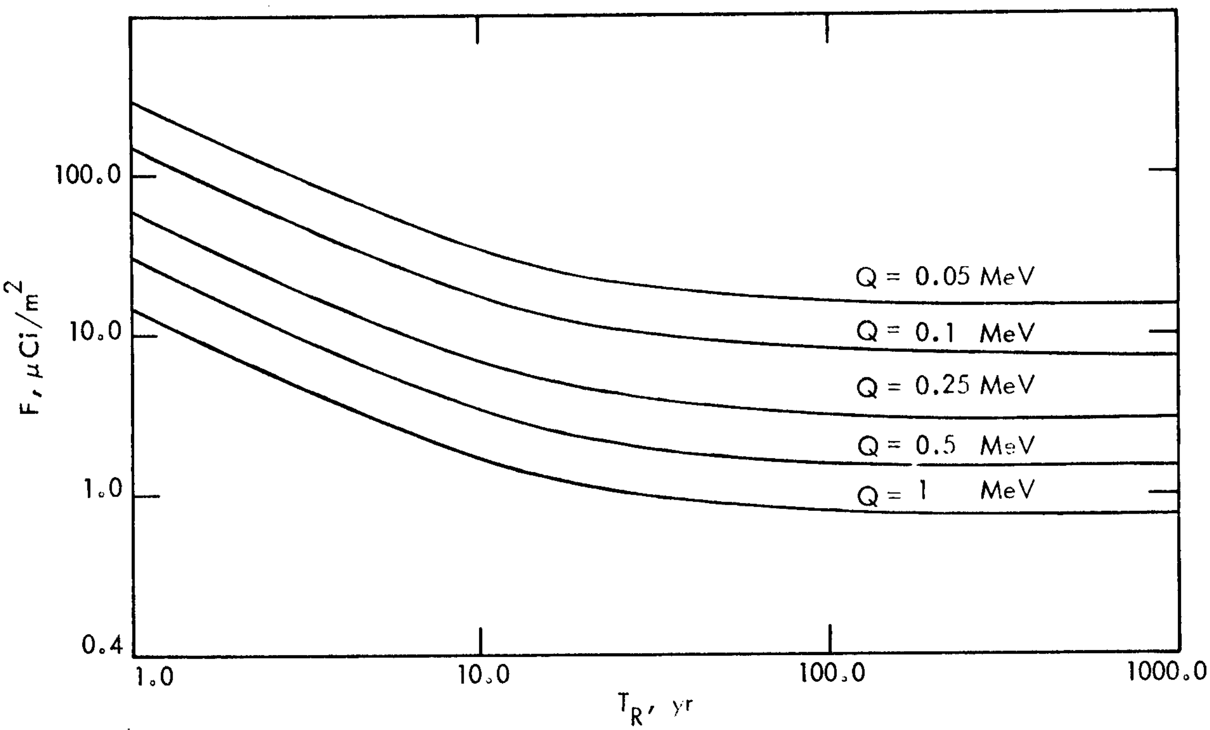

Fig. 3. Deposition required to deliver 1 rad via the soil-root system to tissue for several values of Q.

LIST OF SYMBOLS

A ≡ atomic weight
B ≡ daily consumption in nuclei/day
b ≡ daily consumption of milk in liters/day
C_B ≡ concentration in body or tissue
C_S ≡ concentration in soil or forage
D ≡ integrated dose in rads
d ≡ thickness of plow layer in m
F ≡ fallout deposition in $\mu Ci/m^2$
f_B ≡ fraction of ingested nuclide to tissue
f_M ≡ fraction of ingested nuclide to milk per liter per day
f ≡ fraction of nuclide ingested by cow to each g of tissue in man
m ≡ mass of tissue in g
N^* ≡ number of nuclei in F in nuclei/m^2
n_B ≡ number of nuclei per g body or tissue
n_P ≡ number of nuclei per m^2 on forage

$n_S \equiv$ number of nuclei per g soil

$Q \equiv$ energy absorbed in tissue per disintegration in MeV

$T_B \equiv$ biological half-life in yr

$T_E \equiv$ effective half-life in body or tissue in yr

$T_P \equiv$ effective half-life on forage in yr

$T_R \equiv$ radioactive half-life in yr

$T_S \equiv$ effective half-life in soil in yr

$t \equiv$ time in yr

$U \equiv$ uptake rate in nuclei per g tissue per sec

$(UAF) \equiv$ utilized area foraged in m^2/day

$\lambda_E \equiv$ effective decay constant in body or tissue in sec^{-1}

$\lambda_P \equiv$ effective decay constant on forage in sec^{-1}

$\lambda_R \equiv$ radioactive decay constant in sec^{-1}

$\rho \equiv$ density of soil in g/m^3

APPENDIX A

Solution of Eq. 2

$$\frac{dn_B^*}{dt} = U^*(t) - \lambda_E \, n_B^*(t) . \tag{2}$$

Let

$$U^*(t) = U_0^* \, e^{-\lambda_P t} . \tag{3}$$

Then

$$\frac{dn_B^*}{dt} = U_0^* \, e^{-\lambda_P t} - \lambda_E \, n_B^* . \tag{2a}$$

Multiplying by $e^{\lambda_E t}$ and rearranging

$$e^{\lambda_E t} \frac{dn_B^*}{dt} + \lambda_E \, n_B^* \, e^{\lambda_E t} = U_0^* \, e^{\left(\lambda_E - \lambda_P\right) t} \tag{2b}$$

or

$$\frac{d}{dt}\left(e^{\lambda_E t} \, n_B^* \right) = U_0^* \, e^{\left(\lambda_E - \lambda_P\right) t} . \tag{2c}$$

Integrating

$$e^{\lambda_E t} \, n_B^* = \frac{U_0^*}{\lambda_E - \lambda_P} \, e^{\left(\lambda_E - \lambda_P\right) t} + c \tag{2d}$$

at $t = 0$, $n_B^*(t) = 0$, so that

$$c = - \frac{U_0^*}{\lambda_E - \lambda_P} \tag{2e}$$

and the solution is

$$n_B^* = \frac{U_0^*}{\lambda_E - \lambda_P} \left[e^{-\lambda_P t} - e^{-\lambda_E t} \right] . \tag{4}$$

APPENDIX B

Alternate Derivation of Eq. 22

Assume that the specific activity in the tissue is always in equilibrium with that in the soil. Thus,

$$\frac{n_S^*}{n_S} \equiv \frac{n_B^*}{n_B} \quad . \tag{22a}$$

Now

$$n_B = \frac{N_0 \; C_B}{A} \tag{22b}$$

and

$$n_S = \frac{N_0 \; C_S \; \rho d}{A} \quad . \tag{22c}$$

The number of atoms deposited is

$$n_S^*(0) = 16.82 \times 10^{11} \; F \; T_R \; . \tag{22d}$$

Substituting in Eq. 22a and rearranging

$$F = \frac{5.95 \times 10^{-13} \; C_S \; d\rho}{T_R \; C_B} \; n_B^*(0) \; . \tag{22e}$$

We now need to find the initial number of nuclei required to give a dose after 30 yr of D_{30} rads. As before,

$$\frac{dD(t)}{dt} = 1.6 \times 10^{-8} \lambda_R \; Q \; n_B^*(t) \; . \tag{1}$$

Here, however, we assume that the only mode of decay in the soil is radioactive. By the equilibrium condition above, we have

$$n_B^* = n_B^*(0) \; e^{-\lambda_R t} \quad . \tag{22f}$$

Substituting in Eq. 1 and integrating from $t = 0$ to $t = 30$ yr, we have

$$D_{30} = 1.6 \times 10^{-8}\ Q\ n_B^*(0) \left(1 - e^{-\lambda_R t}\right) . \tag{22g}$$

Solving for $n_B^*(0)$ and substituting in Eq. 22e,

$$F = \frac{3.71 \times 10^{-5}\ C_S\ \rho d\ D_{30}}{Q\ T_R\ C_B} \cdot \frac{1}{\left(1 - e^{-\lambda_R t}\right)} . \tag{22h}$$

This agrees with Eq. 22.

APPENDIX C

$1/T_E$ in yr^{-1} for various T_R and T_B.

T_R T_B	2 d	4	6	8	10	15	20
2 d	365	273.8	243.3	228.1	219.0	206.8	200.8
4	273.8	182.5	152.1	136.9	127.8	115.6	109.5
6	243.3	152.1	121.7	106.4	97.3	85.2	79.1
8	228.1	136.9	106.4	91.2	82.1	70.0	63.9
10	219.0	127.8	97.3	82.1	73.0	60.8	54.8
15	206.8	115.6	85.2	70.0	60.8	48.7	42.6
20	200.8	109.5	79.1	63.9	54.8	42.6	36.5
1 mo	194.5	103.2	72.8	57.6	48.5	36.3	30.2
2	188.5	97.2	66.8	51.6	42.5	30.3	24.2
4	185.5	94.2	63.8	48.6	39.5	27.3	21.2
6	184.5	93.2	62.8	47.6	38.5	26.3	20.2
8	184.0	92.8	62.3	47.1	38.0	25.8	19.8
10	183.7	92.4	62.0	46.8	37.7	25.5	19.4
1 yr	183.5	92.2	61.8	46.6	37.5	25.3	19.0
1.5	183.2	91.9	61.5	46.3	37.2	25.0	18.9
2.0	183.0	91.8	61.3	46.1	37.0	24.8	18.7
3.0	182.8	91.6	61.2	46.0	36.8	24.6	18.6
5.0	182.7	91.4	61.0	45.8	36.7	24.5	18.4
7.0	182.6	91.4	61.0	45.8	36.6	24.4	18.4
10.0	182.6	91.4	60.9	45.7	36.6	24.4	18.4
15.0	182.6	91.3	60.9	45.7	36.6	24.4	18.3
20.0	182.6	91.3	60.9	45.7	36.6	24.4	18.3
50.0	182.5	91.3	60.8	45.6	36.5	24.4	18.3
100.0	182.5	91.3	60.8	45.6	36.5	24.3	18.25
300.0	182.5	91.25					
500.0							
1000.0							
5000.0							

$1/T_E$ in yr^{-1} for various T_R and T_B.

T_R \ T_B	1 mo	2	4	6	8	10	1 yr
2 d	194.5	188.5	185.5	184.5	184.0	183.7	183.5
4	103.2	97.2	94.2	93.2	92.8	92.4	92.2
6	72.8	66.8	63.8	62.8	62.3	62.0	61.8
8	57.6	51.6	48.6	47.6	47.1	46.8	46.6
10	48.5	42.5	39.5	83.5	38.0	37.7	37.5
15	36.3	30.3	27.3	26.3	25.8	25.5	25.3
20	30.2	24.2	21.2	20.2	19.8	19.4	19.0
1 mo	24.0	18.0	15.0	14.0	13.5	13.2	13.0
2	18.0	12.0	9.0	8.0	7.5	7.2	7.0
4	15.0	9.0	6.0	5.0	4.5	4.2	4.0
6	14.0	8.0	5.0	4.0	3.5	3.2	3.0
8	13.5	7.5	4.5	3.5	3.0	2.70	2.50
10	13.2	7.2	4.2	3.2	2.70	2.4	2.2
1 yr	13.0	7.0	4.0	3.0	2.50	2.2	2.0
1.5	12.7	6.67	3.67	2.67	2.17	1.87	1.67
2.0	12.5	6.50	3.50	2.50	2.00	1.70	1.50
3.0	12.3	6.33	3.33	2.33	1.83	1.53	1.33
5.0	12.2	6.20	3.20	2.20	1.70	1.40	1.20
7.0	12.1	6.14	3.14	2.14	1.64	1.34	1.14
10.0	12.1	6.10	3.10	2.10	1.60	1.30	1.10
15.0	12.1	6.07	3.07	2.07	1.57	1.27	1.07
20.0	12.1	6.05	3.05	2.05	1.55	1.25	1.05
50.0	12.0	6.02	3.02	2.02	1.52	1.22	1.02
100.0	12.0	6.01	3.01	2.01	1.51	1.21	1.01
300.0		6.00	3.00	2.00	1.50	1.20	1.00
500.0							
1000.0							
5000.0							

$1/T_E$ in yr^{-1} for various T_R and T_B.

T_R \ T_B	1.5 yr	2.0	3.0	5.0	10.0	20.0	30.0
2 d	183.2	183.0	182.8	182.7	182.6	182.6	182.5
4	91.9	91.8	91.6	91.4	91.4	91.3	91.3
6	61.5	61.3	61.2	61.0	60.8	60.9	60.9
8	46.3	46.1	46.0	45.8	45.7	45.7	45.6
10	37.2	37.0	36.8	36.7	36.6	36.6	36.5
15	25.0	24.8	24.6	24.5	24.4	24.4	24.4
20	18.9	18.7	18.6	18.4	18.4	18.3	18.3
1 mo	12.7	12.5	12.3	12.2	12.1	12.1	12.03
2	6.67	6.50	6.33	6.20	6.10	6.05	6.03
4	3.67	3.50	3.33	3.20	3.10	3.05	3.03
6	2.67	2.50	2.33	2.20	2.10	2.05	2.03
8	2.17	2.00	1.83	1.70	1.64	1.55	1.53
10	1.87	1.70	1.53	1.40	1.30	1.25	1.23
1 yr	1.67	1.50	1.33	1.20	1.10	1.05	1.03
1.5	1.33	1.17	1.00	0.867	0.767	0.717	0.700
2.0	1.17	1.00	0.833	.700	.600	.550	.533
3.0	1.00	0.833	.667	.533	.433	.383	.367
5.0	0.867	.700	.533	.400	.300	.250	.233
7.0	.810	.643	.477	.343	.243	.193	.176
10.0	.767	.600	.433	.300	.200	.150	.133
15.0	.734	.567	.400	.267	.167	.117	.100
20.0	.717	.550	.383	.250	.150	.100	.083
50.0	.687	.520	.353	.220	.120	.070	.053
100.0	.677	.510	.343	.210	.110	.060	.043
300.0	.670	.503	.336	.203	.103	.053	.036
500.0	.669	.502	.335	.202	.102	.053	.035
1000.0	0.667	.501	.334	.201	.101	.051	.034
5000.0		0.500	0.333	0.200	0.100	0.0502	0.033

APPENDIX D

Example: Fallout on Forage

Let us calculate the deposition of I^{131} required to give a 30-yr dose of 1 rad to the thyroid. We have the following parameters:

$$T_R = 8 \text{ days} \qquad f_M = 0.01$$
$$T_B = 100 \text{ days} \qquad f_B = 0.3$$
$$Q = 0.3 \text{ MeV} \qquad m_B = 20 \text{ g}$$

Thus

$$f = \frac{(0.01)(0.03)}{20} = 1.5 \times 10^{-4} \text{ fract/gB} .$$

From Appendix C,

$$1/T_E = 47.1/\text{yr} .$$

From Fig. 2, for Q = 1 MeV

$$F(1 \text{ MeV}) = 0.013$$

For Q = 0.3 MeV

$$F(0.3) = \frac{0.013}{0.3} = 0.043$$

Since $T_R < 4$ mo, we need the T_R correction factor, in this case 2.73. Thus, the required deposition is

$$F = (2.73)(0.043) = 0.12 \mu\text{Ci/m}^2 .$$

One can also ask what would be the 30-yr dose resulting from a deposition of $1 \mu\text{Ci/m}^2$ of I^{131}. From above,

$$F(1 \text{ rad}) = 0.12 \mu\text{Ci/m}^2 .$$

Since F is linear in D_{30}, we have

$$D_{30}(1\mu Ci/m^2) = \frac{(1\mu Ci/m^2)(1\ rad)}{0.12\mu Ci/m^2} = 8.33\ rads.$$

Example: Fallout Mixed With Soil

Let us calculate the deposition of Fe^{55} required to give a 30-yr dose of 1 rad to the liver. From the ICRP handbook,

$$Q = 0.0065\ MeV$$
$$C_B = 1.85 \times 10^{-4}$$
$$T_R = 2.6\ yr$$
$$T_B = 1.52\ yr$$

Assuming

$$\rho = 2 \times 10^6\ g/m^3$$
$$d = 0.2\ m$$
$$C_S = 0.04$$

we have, using Eq. 21

$$F = \frac{(1)(3.7 \times 10^{-5})(2 \times 10^6)(0.2)(0.04) \times 10^3}{(0.0065)(1.85 \times 10^{-4})\left[2.6\left(1 - e^{-20.8/2.6}\right) - \frac{(2.6)(1.52)}{(2.6 + 1.52)}\left(1 - e^{-20.8/0.955}\right)\right]}$$

$$= 300\ mCi/m^2\ .$$

Using Fig. 3 for $Q = 1.0$ MeV and $C_S = C_B$,

$$F(1.0,\ C_S = C_B) = 5.8\mu Ci/m^2$$

$$F(0.0065,\ 0.04,\ 1.85 \times 10^{-4}) = \frac{(5.8)(0.04)}{(0.0065)(1.85 \times 10^{-4})} = 193\ mCi/m^2\ .$$

Thus the assumption that $T_B \longrightarrow 0$ minimizes the deposition required to produce a given dose.

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