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METHOD OF CALCULATING INFINITY GAMMA DOSE FROM BETA MEASUREMENTS ON GUMMED FILM

Naomi A. Hallden
John H. Harley

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Analytical Branch
Health and Safety Laboratory

The basic fallout datum obtained at the Health and Safety Laboratory is the beta activity of mixed fission products collected on gummed film in units of d/m/sq.ft./24 hrs. In comparing various samples each sample is assumed to come from a specific burst and the activity is extrapolated to a fixed date. In addition, an efficiency factor of 1.6 should be included to correct for loss by the gummed film. This factor is based on experimental data obtained during an 84 week period at New York.

It is not possible to make a direct measurement of the gamma dose resulting from normal fallout away from the test site since the activity is very low; however, it is desirable to have an estimate of the cumulative gamma dose which might arise from continued fallout in a given area. The following calculations are designed to allow an estimate of gamma dose based on measurement of the beta activity in fallout.

There are certain assumptions made which are justified in the text where required. These are

1) The activity is considered to come from a smooth infinite plane source.

2) The activity is uniformly distributed over this plane at any given location.

3) The majority of the gamma dose is received from direct radiation and no scatter contribution is included.

4) The dose can be based on an average gamma energy rather than a summation of individual values.

5) The beta activity decays according to the $T^{-1.2}$ rule.

6) The isotopic abundance follows the values given by Hunter and Ballou for slow fission.

The first assumption gives a high estimate for dose since the activity is not entirely at the surface. This high estimate is compensated for qualitatively by ignoring scatter contribution (Assumption 3). The assumption of uniform distribution is necessary for simplicity and is justified in estimating an average dose. The other three assumptions will be treated in the development.

Derivation of Area Function

It is required to calculate the radiation incident on an elemental volume dAdl three feet above an infinite plane of uniform gamma activity.

If we consider an infinitesimal plane source, ds, (Fig. 1) having a length $rdr/\sqrt{r^2 - 9}$ and width $\sqrt{r^2 - 9}\ d\phi$, its area is

$$ds = \frac{rdr}{\sqrt{r^2 - 9}} \cdot \sqrt{r^2 - 9}\ d\phi = rdrd\phi$$

The area of the ring at a distance r from the elemental volume is,

$$\text{Area} = 2\pi\ rdr$$

The fraction of the radiation (dI) from the area 2π rdr adsorbed in the elemental volume is

$$\frac{dI}{I_i} = (2\pi\, rdr)(e^{-\mu_a r})\left(\frac{dA\cos\theta}{4\pi r^2}\right)\left(\frac{\mu_a dl}{\cos\theta}\right)$$

where the four parenthetical terms are,

1. The area of the ring.
2. The attenuation in air (μa = air absorption coefficient).
3. The fraction of the spherical radiation front intercepted by dA.
4. The fraction of the incident radiation absorbed in the elemental volume.

If our infinite plane is emitting n_t gamma photons per square foot per second at time t, and the average energy of the photons is E_o, the radiation flux incident on the element volume is,

$$\frac{dI}{dAdl} = n_t E_o \cdot \frac{1}{2} \cdot \frac{e^{-\mu_a r}}{r} \mu_a dr \qquad \text{Mev/ft}^3\text{/sec}$$

Then,

$$\frac{I}{\Delta V} = \int_3^{\infty} \frac{n_t E_o}{2} \frac{e^{-\mu_a r}}{r} \mu_a dr$$

Dividing by μa

$$\frac{I}{\Delta V \mu_a} = \int_3^{\infty} \frac{n_t E_o}{2} \frac{e^{-\mu_a r}}{\mu_a r} d(\mu_a r)$$

This is of the form,

$$\frac{I}{\Delta V \mu_a} = \frac{n_t E_o}{2} \int_{3\mu}^{\infty} \cdot \frac{e^{-x}}{x} dx = -E_i (-3\mu)$$

which can be evaluated from "Tables of Sine, Cosine and Exponential Integrals, Vol. II", Federal Works Agency, New York, 1940. The contribution from circles of various radii is given in Appendix A.

Derivation of Dose Function

The absorption factor, μa, is equal to 1.06 x 10^{-3} ft.$^{-1}$ for the average gamma energy of the mixed fission products. This absorption coefficient is for the loss of Compton electrons in air, the only significant absorption loss. This gives a value of 5.30 for the exponential integral.

$$\frac{I}{\Delta V \mu_a} = \frac{5.30\, n_t E_o}{2} = 2.65\, n_t E_o \qquad \text{Mev/ft.}^2\text{/sec}$$

The dose would be

$$\frac{I}{\Delta V} = 2.65 \; n_t \, E_o \, \mu_a \qquad \text{Mev/ft.}^3\text{/sec}$$

$$= \frac{.00281 \;\Big|\; n_t \, E_o \;\Big|\; \quad \;\Big|\; 60 \;\Big|\; 1.6 \times 10^{-6} \;\Big|\;}{\quad \;\Big|\; \quad \;\Big|\; 28,320 \;\Big|\; \quad \;\Big|\; 1.29 \times 10^{-3} \;\Big|\; 100}$$

$$= 7.38 \times 10^{-11} \; n_t \, E_o \text{ rads/minute}$$

7.38×10^{-8}

Since the usual activity measurement is d/m, N_t will be defined as 60 n_t, and the

$$\text{Dose Rate} = 1.23 \times 10^{-9} \; N_t E_o \text{ millirads/minute}$$

where N_t is photons per minute at time t.

Energy Function

The contribution of the various isotopes as a function of time is given in Appendix B. These values are calculated from the date of Hunter and Ballou for slow neutron fission. The weighted average gamma energy for various times is given in the following table:

Days After Burst	Average E_γ
1	0.70
2	0.49
3	0.54
4	0.54
5	0.47
6	0.49
8	0.50
10	0.52
30	0.52
60	0.52
120	0.57
365	0.53
730	0.48
3650	0.59

The value of μ_a is relatively constant within 20% of the maximum value over the gamma energy range of 0.13 to 1.9 Mev. This range includes all of the important gamma contributions. The average E γ from the preceding table is 0.54 Mev, and a value of μ_a of 1.06×10^{-3} ft^{-1} is justified for all calculations.

For simplicity, it is desirable to use a single average energy. From the table, it is apparent that the error involved in using 0.54 Mev is negligible in comparison with other uncertainties in calculation.

Since the distribution of gamma energy with mass is apparently random, the difference in energy distribution between slow and fast fission has been ignored.

This allows the simplification of the dose formula to,

$$\text{Dose Rate} = 6.64 \times 10^{-10} N_t \qquad \text{millirads/minute}$$

where N_t is the number of gamma d/m/ft^2 at time t.

Derivation of Time Function

Assuming beta decay follows the $t^{-1.2}$ law, it is possible to calculate the total number of beta disintegrations which will result from a given sample,

$$\sum N = 7200\, N_c \frac{(t_c - t_b)^{1.2}}{(t_s - t_b)^{0.2}}$$

where

$\sum N$ = Total β disintegrations/ft^2 from sampling day to infinity.

N_c = β d/m/ft^2 on counting day.

t_b = Burst day.

t_c = Counting day.

t_s = Sampling day.

If there was a 1:1 correspondence in β and γ d/m, the infinity dose could be calculated from,

$$\text{Dose Rate} = 6.64 \times 10^{-10} N_t \text{ millirads/minute}$$

by substituting $\sum N$ for N_t,

$$\text{Dose} = 6.64 \times 10^{-10} \sum N \text{ millirads}$$

However, as shown in the following table, the β/γ ratio is a marked function of time:

Days After Burst	β/γ
1	1.01
2	0.94
3	1.00
4	1.01
5	1.00
6	1.10
8	1.18
10	1.27
30	1.66
60	1.63
120	1.64
365	2.98
730	5.15
3650	3.92

These ratios are calculated from the data in Appendix B by omitting gaseous isotopes from both β and γ totals and omitting the iodine isotopes from the β total.

Obviously, a large error would be introduced by assuming an average β/γ ratio. The following method is proposed:

1. The integrated average β/γ ratio for the first 120 days is 1.2. Calculate total β disintegrations per square foot from arrival time to 120 days after burst by integration. Divide this number by 1.2 to give total γ disintegrations in 120 days.

2. In Appendix C it is calculated that at 120 days, there are 1.62×10^5 atoms that will undergo gamma decay for every β d/m at 120 days. Calculate the β d/m at 120 days and multiply by 1.62×10^5 to give total γ disintegrations after 120 days.

3. Add 1 and 2 to obtain $\sum N$ in the expression

$$\text{Dose} = 6.64 \times 10^{-10} \sum N \quad \text{millirads}$$

If a time differing from 120 days is required, the relationship is shown in Fig. 2.

<u>Example of Suggested IBM Calculation</u>

Assume	Burst Date	087
	Sample Date	091
	Count Date	097

Activity on 097 $= 10^4$ d/m/ft^2

1. Total β disintegrations - Sample date to infinity

$$N_1 = 7200\, a_c \frac{(t_c - t_b)^{1.2}}{(t_s - t_b)^{0.2}}$$

$$= \frac{(7.2 \times 10^3)(10^4)(10)^{1.2}}{(4)^{0.2}}$$

$$= 8.68 \times 10^8 \ \text{d/ft}^2$$

2. Beta d/m 120 days after burst

$$A_{120} = A_c \frac{(120)^{-1.2}}{(t_c - t_b)^{-1.2}}$$

$$= 10^4 \left(\frac{10}{120}\right)^{1.2}$$

$$= 5.10 \times 10^2 \text{ d/m}$$

3. Total β disintegrations - 120 days to infinity

$$N_2 = 7200 \; A_{120} \; (120)^{1.0}$$

$$= 8.65 \times 10^5 \; A_{120}$$

$$= 4.41 \times 10^8 \text{ d/ft}^2$$

4. Beta disintegrations - Sample date to 120 days. This may be formulated

$$N_1 - N_2 = 7200 \; A_c \; (t_c - t_b)^{1.2} \left[\frac{1}{(t_s - t_b)^{0.2}} - \frac{1}{(120)^{0.2}} \right]$$

or from 1 and 3

$$N_1 - N_2 = (8.68 - 4.41) \times 10^8$$

$$= 4.27 \times 10^8 \text{ d/ft}^2$$

5. Gamma disintegrations - Sample date to 120 days

$$N_3 = \frac{(4.24 \times 10^8)}{1.2}$$

$$= 3.56 \times 10^8 \ d/ft^2$$

6. Gamma disintegrations - 120 days to infinity

$$N_4 = (5.10 \times 10^2)(1.62 \times 10^5)$$

$$= 8.25 \times 10^7 \ d/ft^2$$

7. Gamma disintegrations - Sample date to infinity

$$\sum N = 3.56 \times 10^8 + 0.82 \times 10^8$$

$$= 4.38 \times 10^8 \ d/ft^2$$

8. Gamma dose

$$\text{Dose} = (6.64 \times 10^{-10})(4.38 \times 10^8)$$

$$= 2.91 \times 10^{-1}$$

$$= 0.29 \text{ millirads}$$ or about 3 mrad for 10^6 dpm/ft² on count date - 10 days after burst

Note that about 80% of the dose is received in the first 4 months after fallout.

using $t_s = t_c = t_b + 1$ day gives
2.8 mrad for 10^6 dpm/ft² @ 1 day

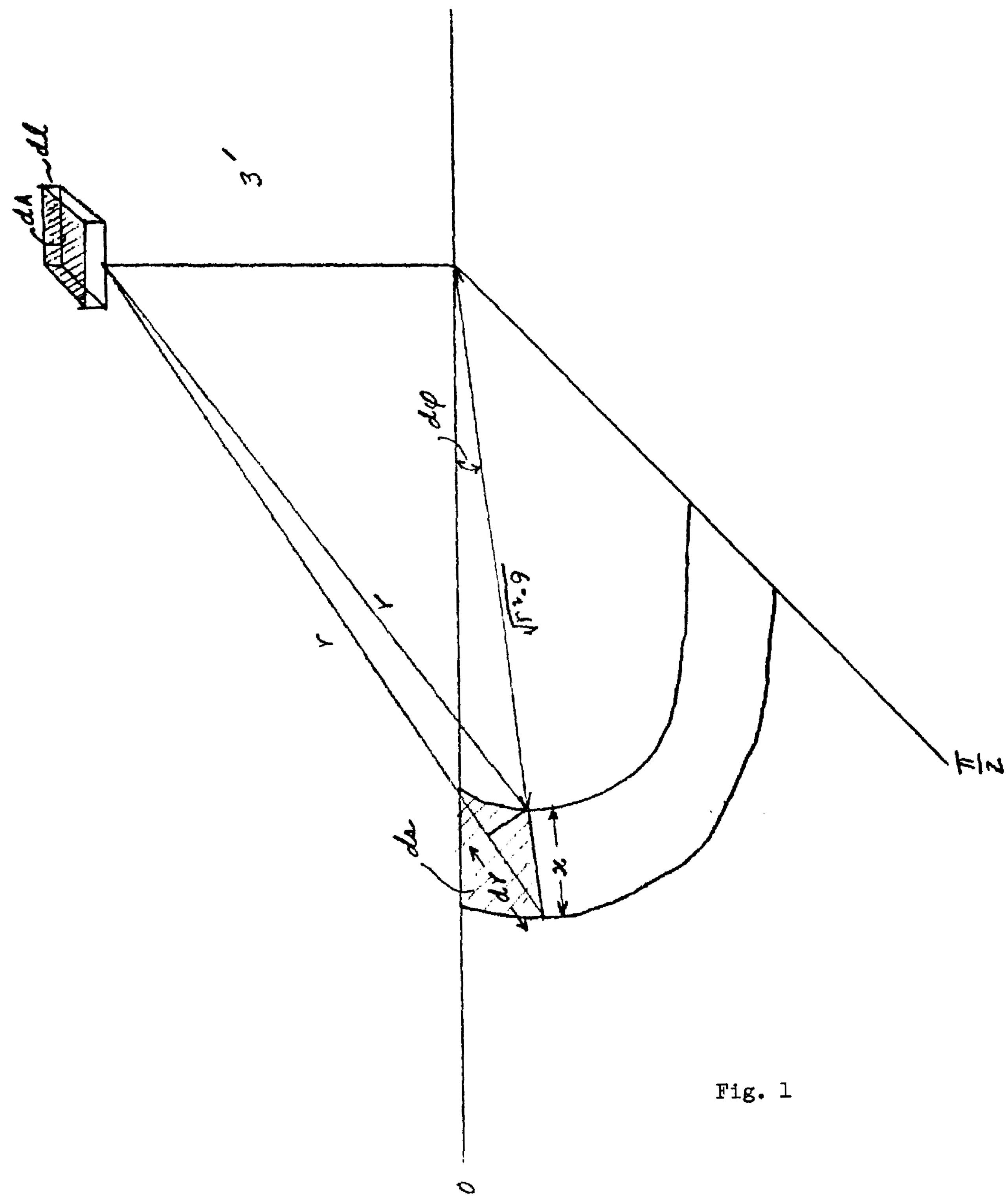

Fig. 1

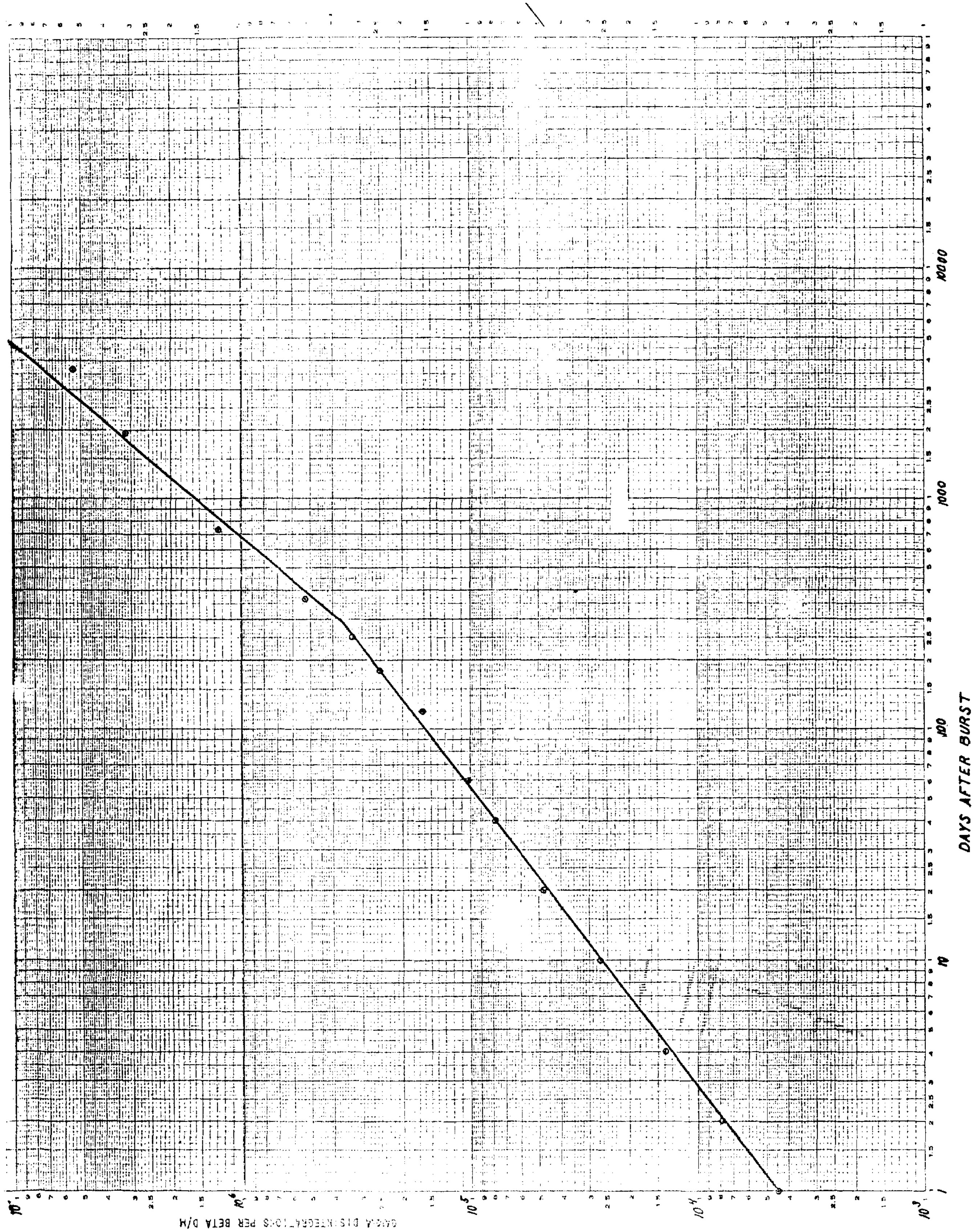
DAYS AFTER BURST
GAMMA DISINTEGRATIONS PER BETA D/M
10
100
1000
10000

Fig. 2

APPENDIX A

The contribution to the infinite plane dose of radiation from circles of various radii may be calculated from,

$$\frac{I}{\Delta V \mu_a} = \int_{.3\mu}^{d} \frac{n_o \quad E_o}{2} \quad \frac{e^{-\mu_a r}}{\mu_a r} \, dr$$

The values obtained from various radii are shown in the table as per cent of the infinite plane dose.

Radius	% of Infinite Plane Dose
10	26
50	54
100	67
500	90
∞	100

APPENDIX B

β and γ Contributions at Various Times

The β and γ contributions for various times are shown in the following table:

1. The total β activity is taken as 10^6 d/m at each specified time after fission.

2. The isotopes and their percent contributions to total activity are taken from the data of Hunter and Ballou.

3. β and γ energies and the decay schemes from all isotopes are taken from NBS Circular 499, and supplements, and Nuclear Science Abstracts through December 1955.

4. The disintegration rate associated with every β and γ energy is calculated from the preceding data.

5. When there is a questionable decay scheme the isotope is asterisked where it appears first.

1 Day

Isotope	% Total Activity	Total Activity d/m	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
I^{131}	1.0	1.0×10^4	0.60 0.32	85 15	8.5×10^3 1.5×10^3	0.36 0.64	85 15	8.5×10^3 1.5×10^3
Ba^{140}	1.2	1.2×10^4	0.48 1.02	40 60	4.8×10^3 7.2×10^3	0.54	40	4.8×10^3
La^{141}	1.36	1.36×10^4	2.4 0.9	95 5	1.29×10^4 6.8×10^2	1.5	5	6.8×10^2
Rh^{105}	1.30	1.3×10^4	0.57 0.25	96 4	1.25×10^4 5.2×10^2	0.32	4	5.2×10^2
Pm^{149}	1.4	1.4×10^4	0.97	100	1.4×10^4	0.285	100	1.4×10^4
* Te^{132}	2.6	2.6×10^4	0.28	50	1.3×10^4	0.22	50	1.3×10^4
I^{132}	2.7	2.7×10^4	0.73 0.90 1.16 1.53 2.12	15 20 23 24 18	4.05×10^3 5.4×10^3 6.2×10^3 6.48×10^3 4.96×10^3	0.96 0.53 1.40 0.78 0.67	23 24 15 18 18	6.2×10^3 6.48×10^3 4.05×10^3 4.96×10^3 4.96×10^3
1 Y^{91}	3.00	3.0×10^4	None	--	--	0.55	100	3.0×10^4
Pr^{145}	2.90	2.9×10^4	3.2	100	2.9×10^4	None	--	--
* Y^{92}	4.0	4.0×10^4	3.6	100	4.0×10^4	1.0 0.6	50 50	2.0×10^4 2.0×10^4
Mo^{99}	4.6	4.6×10^4	0.45 1.23	15 85	6.9×10^3 3.91×10^4	0.78 0.14	15 85	6.9×10^3 3.91×10^4
* I^{135}	4.7	4.7×10^4	0.47 1.0 1.4	35 40 25	1.65×10^4 1.88×10^4 1.17×10^4	None	--	--

Isotope	% Total Activity	Total Activity d/m	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Sr^{91}	6.7	6.7×10^4	1.3	40	2.68×10^4	1.3	40	2.68×10^4
			3.2	60	4.02×10^4			
* Ce^{143}	6.8	6.8×10^4	1.36	100	6.8×10^4	0.5	100	6.8×10^4
* I^{133}	7.3	7.3×10^4	1.4	94	6.86×10^4	0.53	50	3.65×10^4
			0.5	6	4.4×10^3			
* Y^{93}	7.6	7.6×10^4	3.1	100	7.6×10^4	0.7	100	7.6×10^4
Zr^{97}	8.9	8.9×10^4	2.2	100	8.9×10^4	0.8	100	8.9×10^4
Cb^{97}	9.7	9.7×10^4	1.4	100	9.7×10^4	0.78	100	9.7×10^4
* [illegible]	0.3		(Unknown decay process)			--	--	--
[illegible]	0.6	6.0×10^3	2.0	55	3.3×10^3	0.70	45	2.7×10^3
			1.4	45	2.7×10^3	0.16	45	2.7×10^3
* I[illegible]	0.1	1.0×10^3	1.5	100	1.0×10^3	1.1	100	1.0×10^3
Nd^{146}	0.6	(Stable isotope)						
* La^{140}	0.4	4.0×10^3	1.32	70	2.8×10^3	1.6	10	4.0×10^2
			1.67	20	8.0×10^2	0.49	20	8.0×10^2
			2.26	10	4.0×10^2	0.82	70	2.8×10^3
Pr^{143}	0.4	4.0×10^3	0.93	100	4.0×10^3	None	--	--
Ce^{141}	0.6	6.0×10^3	0.41	70	4.2×10^3	0.141	70	4.2×10^3
			0.56	30	1.8×10^3			
* Ru^{103}	0.2	2.0×10^3	0.22	90	1.8×10^3	0.495	90	1.8×10^3
			0.11	10	2.0×10^2	0.610	10	2.0×10^2

Isotope	% Total Activity	Total Activity d/m	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Rh^{103}	0.2	2.0×10^3	None	--	--	0.04	100	2.0×10^3
Y^{91}	0.2	2.0×10^3	1.54	100	2.0×10^3	None	--	--
Zr^{95}	0.3	3.0×10^3	0.4	100	3.0×10^3	0.71	100	3.0×10^3
Sr^{89}	0.2	2.0×10^3	1.50	100	2.0×10^3	None	--	--

2 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
I^{135}	1.0	0.47 1.00 1.4	35 40 25	3.5×10^3 4.0×10^3 2.5×10^3	None	--	--
$_{1}Y^{91}$	1.36	None	--	--	0.55	100	1.36×10^4
Ce^{141}	1.36	0.41 0.56	70 30	9.52×10^3 4.08×10^3	0.141	70	9.52×10^3
Nd^{147}	1.40	0.4 0.9	40 60	5.6×10^3 8.4×10^3	0.58	40	5.6×10^3
Pr^{143}	1.65	0.93	100	1.65×10^4	None	--	--
La^{140}	1.75	1.32 1.67 2.26	70 20 10	1.225×10^4 3.5×10^3 1.75×10^3	1.6 0.49 0.82	10 20 70	1.75×10^3 3.5×10^3 1.225×10^4
Rh^{105}	2.1	0.57 0.25	96 4	2.02×10^4 8.4×10^2	0.32	4	8.4×10^2
I^{131}	2.35	0.60 0.32	85 15	2.0×10^4 3.5×10^3	0.36 0.64	85 15	2.0×10^4 3.5×10^3
Pm^{149}	2.55	0.97	100	2.55×10^4	0.29	100	2.55×10^4
Ba^{140}	2.95	0.48 1.02	40 60	1.18×10^4 1.77×10^4	0.54	40	1.18×10^4
Sr^{91}	3.0	1.3 3.2	40 60	1.2×10^4 1.8×10^4	1.3	40	1.2×10^4
Y^{93}	3.65	3.1	100	3.65×10^4	0.7	100	3.65×10^4
Te^{132}	5.30	0.28	50	2.65×10^4	0.22	50	2.65×10^4

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
I^{133}	5.5	0.73	15	8.25×10^3	0.96	23	1.265×10^4
		0.90	20	1.1×10^4	0.53	24	1.32×10^4
		1.16	23	1.26×10^4	1.40	15	8.25×10^3
		1.53	24	1.32×10^4	0.78	18	9.9×10^3
		2.12	18	9.9×10^3	0.67	18	9.9×10^3
Zr^{97}	8.3	2.2	100	8.3×10^4	0.8	100	8.3×10^4
I^{133}	8.5	1.4	94	7.99×10^4	0.53	50	4.25×10^4
		0.5	6	5.1×10^3			
Cb^{97}	9.0	1.4	100	9.0×10^4	0.78	100	9.0×10^4
Mo^{99}	9.0	0.45	15	1.35×10^4	0.78	15	1.35×10^4
		1.23	85	7.65×10^4	0.14	85	7.65×10^4
Ce^{143}	10.0	1.36	100	1.0×10^5	0.5	100	1.0×10^5
$_2Rh^{101}$	0.9	2.0	55	4.95×10^3	0.70	45	4.05×10^3
		1.4	45	4.05×10^3	0.16	45	4.05×10^3
Y^{92}	0.1	3.6	100	1.0×10^3	1.0	50	5.0×10^2
					0.6	50	5.0×10^2
Pr^{145}	0.2	3.2	100	2.0×10^3	None	--	--
Ru^{103}	0.5	0.22	90	4.5×10^3	0.495	90	4.5×10^3
		0.11	10	5.0×10^2	0.610	10	5.0×10^2
$_1Rh^{103}$	0.5	None	--	--	0.04	100	5.0×10^3
Zr^{95}	0.6	0.4	100	6.0×10^3	0.71	100	6.0×10^3
$_2Y^{91}$	0.6	0.4	100	6.0×10^3	0.71	100	6.0×10^3
Sr^{89}	0.6	1.50	100	6.0×10^3	None	--	--

<u>**3 Days**</u>

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Sr^{89}	1.00	1.50	100	1.0×10^4	None	--	--
Y^{91}	1.05	1.54	100	1.05×10^4	None	--	--
Zr^{95}	1.10	0.4	100	1.10×10^4	0.71	100	1.10×10^4
Sr^{91}	1.05	1.3 3.2	40 60	4.2×10^3 6.3×10^3	1.3	40	4.2×10^3
Y^{93}	1.25	3.1	100	1.25×10^4	0.7	100	1.25×10^4
Rh^{105}	2.18	0.57 0.25	96 4	2.09×10^4 9.0×10^2	0.32	4	9.0×10^2
Ce^{141}	2.23	0.41 0.56	70 30	1.561×10^4 6.69×10^3	0.141	70	1.56×10^4
Nd^{147}	2.23	0.4 0.9	40 60	8.92×10^3 1.34×10^4	0.58	40	8.93×10^3
Pm^{149}	2.90	0.97	100	2.9×10^4	0.29	100	2.9×10^4
Pr^{143}	3.30	0.93	100	3.3×10^4	None	--	--
La^{140}	3.6	1.32 1.67 2.26	70 20 10	2.52×10^4 7.2×10^3 3.6×10^3	1.6 0.49 0.82	10 20 70	3.6×10^3 7.2×10^3 2.52×10^4
I^{131}	2.35	0.60 0.32	85 15	2.0×10^4 3.5×10^3	0.36 0.64	85 15	2.0×10^4 3.5×10^3
Ba^{140}	4.6	0.48 1.02	40 60	1.84×10^4 2.76×10^4	0.54	40	1.84×10^4
Zr^{97}	5.30	2.2	100	5.3×10^4	0.8	100	5.3×10^4
Cb^{97}	5.80	1.4	100	5.8×10^4	0.78	100	5.8×10^4

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
I^{133}	6.6	1.4	94	6.2×10^4	0.53	50	3.3×10^4
		0.5	6	4.0×10^3			
Te^{132}	7.00	0.28	50	3.5×10^4	0.22	50	3.5×10^4
I^{132}	7.30	0.73	15	1.1×10^4	0.96	23	1.68×10^4
		0.90	20	1.46×10^4	0.53	24	1.75×10^4
		1.16	23	1.68×10^4	1.40	15	1.1×10^4
		1.53	24	1.75×10^4	0.78	18	1.31×10^4
		2.12	18	1.31×10^4	0.67	18	1.31×10^4
Ce^{145}	10.0	1.36	100	1.0×10^5	0.5	100	1.0×10^5
Mo^{99}	11.5	0.45	15	1.73×10^4	0.78	15	1.73×10^4
		1.23	85	9.78×10^4	0.14	85	9.78×10^4

4 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Rh^{103}	1.15	None	--	--	0.04	100	1.15×10^4
Ru^{103}	1.2	0.22 0.11	90 10	1.08×10^4 1.2×10^3	0.495 0.610	90 10	1.08×10^4 1.2×10^3
Sr^{89}	1.3	1.5	100	1.3×10^4	None	--	--
Y^{91}	1.4	1.54	100	1.4×10^4	None	--	--
Zr^{95}	1.50	0.4	100	1.5×10^4	0.71	100	1.5×10^4
Rh^{105}	1.90	0.57 0.25	96 4	1.82×10^4 8.0×10^2	0.32	4	8.0×10^2
Zr^{97}	2.7	2.2	100	2.7×10^4	0.8	100	2.7×10^4
Nd^{147}	2.85	0.4 0.9	40 60	1.14×10^4 1.71×10^4	0.58	40	1.14×10^4
Pm^{149}	2.85	0.97	100	2.85×10^4	0.29	100	2.85×10^4
Ce^{141}	3.0	0.41 0.56	70 30	2.1×10^4 9.0×10^3	0.141	70	2.1×10^4
I^{133}	4.30	1.4 0.5	94 6	4.04×10^4 2.6×10^3	0.53	50	2.15×10^4
I^{131}	4.60	0.60 0.32	85 15	3.91×10^4 6.9×10^3	0.36 0.64	85 15	3.91×10^4 6.9×10^3
Pr^{143}	4.80	0.93	100	4.8×10^4	None	--	--
La^{140}	5.4	1.32 1.67 2.26	70 20 10	3.78×10^4 1.08×10^4 5.4×10^3	1.6 0.49 0.82	10 20 70	5.4×10^3 1.08×10^4 3.78×10^4

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Ba^{140}	6.00	0.48 1.02	40 60	2.4×10^4 3.6×10^4	0.54	40	2.4×10^4
Te^{132}	7.7	0.28	50	3.85×10^4	0.22	50	3.85×10^4
I^{132}	8.00	0.73 0.90 1.16 1.53 2.12	15 20 23 24 18	1.2×10^4 1.6×10^4 1.84×10^4 1.92×10^4 1.44×10^4	0.96 0.53 1.40 0.78 0.67	23 24 15 18 18	1.84×10^4 1.92×10^4 1.2×10^4 1.44×10^4 1.44×10^4
Ce^{143}	8.40	1.36	100	8.4×10^4	0.5	100	8.4×10^4
Mo^{99}	12.3	0.45 1.23	15 85	1.845×10^4 1.045×10^5	0.78 0.14	15 85	1.845×10^4 1.045×10^5
Cb^{97}	2.95	1.4	100	2.95×10^4	0.78	100	2.95×10^4
$_2Te^{131}$	0.7	2.0 1.4	55 45	3.85×10^3 3.15×10^3	0.70 0.16	45 45	3.5×10^3 3.15×10^3
Y^{93}	0.3	3.1	100	3.0×10^3	0.7	100	3.0×10^3
Sr^{91}	0.2	1.3 3.2	40 60	8.0×10^2 1.2×10^3	1.3	40	8.0×10^2
$_1Y^{91}$	0.1	None	--	—	0.55	100	1.0×10^3
$_2Cb^{95}$	0.1	0.146	100	1.0×10^3	0.76	100	1.0×10^3
Ce^{144}	0.3	0.3					
Pr^{144}	0.3	3.0 2.3 0.8	95 2 3	2.85×10^3 6.0×10^2 9.0×10^2	0.696 2.2 1.5	2.0 2.1 0.9	6.0×10^2 6.0×10^2 2.7×10^2

5 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Cb^{97}	1.3	1.4	100	1.3×10^4	0.78	100	1.3×10^4
Zr^{97}	1.3	2.2	100	1.3×10^4	0.8	100	1.3×10^4
$_1Rh^{103}$	1.43	None	--	--	0.04	100	1.43×10^4
Ru^{103}	1.48	0.22	90	1.33×10^4	0.495	90	1.33×10^4
		0.11	10	1.48×10^3	0.610	10	1.48×10^3
Rh^{105}	1.55	0.57	96	1.49×10^4	0.32	4	6.0×10^3
		0.25	4	6.0×10^3			
Sr^{89}	1.6	1.50	100	1.6×10^4	None	--	--
$_2Y^{91}$	1.75	1.54	100	1.75×10^4	None	--	--
Zr^{95}	1.85	0.4	100	1.85×10^4	0.71	100	1.85×10^4
Pm^{149}	2.50	0.97	100	2.5×10^4	0.285	100	2.5×10^4
I^{133}	7.3	1.4	94	6.86×10^4	0.53	50	3.65×10^4
		0.5	6	4.4×10^3			
Nd^{147}	3.40	0.41	70	2.38×10^4	0.141	70	2.38×10^4
		0.56	30	1.02×10^4			
Ce^{141}	3.65	0.41	70	2.55×10^4	0.141	70	2.55×10^4
		0.56	30	1.10×10^4			
I^{131}	5.40	0.60	85	4.59×10^4	0.36	85	4.59×10^4
		0.32	15	8.1×10^3	0.64	15	8.1×10^3
Po^{143}	6.1	0.93	100	6.1×10^4	None	--	--

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Ce^{143}	6.50	1.36	100	6.5×10^4	0.5	100	6.5×10^4
La^{140}	6.9	1.32	70	4.83×10^4	1.6	10	6.9×10^3
		1.67	20	1.38×10^4	0.49	20	1.38×10^4
		2.26	10	6.9×10^3	0.82	70	4.83×10^4
Ba^{140}	7.2	0.48	40	2.88×10^4	0.54	40	2.88×10^4
		1.02	60	4.32×10^4			
Te^{132}	7.70	0.28	50	3.85×10^4	0.22	50	3.85×10^4
I^{132}	8.00	0.73	15	1.2×10^4	0.96	23	1.84×10^4
		0.90	20	1.6×10^4	0.53	24	1.92×10^4
		1.16	23	1.84×10^4	1.40	15	1.20×10^4
		1.53	24	1.92×10^4	0.78	18	1.44×10^4
		2.12	18	1.44×10^4	0.67	18	1.44×10^4
Mo^{99}	12.0	0.45	15	1.8×10^4	0.78	15	1.8×10^4
		1.23	85	1.02×10^5	0.14	85	1.02×10^5

6 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Rh^{105}	1.20	0.57 0.25	96 4	1.15×10^4 5.0×10^2	0.32	4	5.0×10^2
X^{133}	1.5	1.4 0.5	94 6	1.41×10^4 9.0×10^2	0.53	50	7.5×10^3
Rh^{103}	1.67	None	—	--	0.04	100	1.67×10^4
Ru^{103}	1.70	0.22 0.11	90 10	1.53×10^4 1.7×10^3	0.495 0.610	90 10	1.53×10^4 1.70×10^3
Sr^{89}	1.90	1.5	100	1.9×10^4	None	--	--
$_2Y^{91}$	2.10	1.54	100	2.1×10^4	None	--	—
Zr^{95}	2.20	0.4	100	2.2×10^4	0.71	100	2.2×10^4
Pm^{149}	2.10	0.97	100	2.10×10^4	0.285	100	2.10×10^4
Nd^{147}	3.80	0.4 0.9	40 60	1.52×10^4 2.28×10^4	0.58	40	1.52×10^4
Ce^{141}	4.2	0.41 0.56	70 30	2.94×10^4 1.26×10^4	0.141	70	2.94×10^4
Ce^{143}	4.6	1.36	100	4.6×10^4	0.5	100	4.6×10^4
I^{131}	5.90	0.60 0.32	85 15	5.02×10^4 8.8×10^3	0.36 0.64	85 15	5.02×10^4 8.8×10^3
Pr^{143}	7.20	0.93	100	7.2×10^4	None	--	--
Te^{132}	7.4	0.28	50	3.7×10^4	0.22	50	3.7×10^4

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
I^{132}	7.8	0.73	15	1.17×10^4	0.96	23	1.80×10^4
		0.90	20	1.56×10^4	0.53	24	1.87×10^4
		1.16	23	1.80×10^4	1.40	15	1.17×10^4
		1.53	24	1.87×10^4	0.78	18	1.40×10^4
		2.12	18	1.40×10^4	0.67	18	1.40×10^4
Ba^{140}	8.1	0.48	40	3.24×10^4	0.54	40	3.24×10^4
		1.02	60	4.86×10^4			
La^{140}	8.30	1.32	70	5.81×10^4	1.6	10	8.3×10^3
		1.67	20	1.66×10^4	0.49	20	1.66×10^4
		2.26	10	8.3×10^3	0.82	70	5.81×10^4
Mo^{99}	11.0	0.45	15	1.65×10^4	0.78	15	1.65×10^4
		1.23	85	9.35×10^4	0.14	85	9.35×10^4

8 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Pm^{149}	1.35	0.97	100	1.35×10^{4}	0.285	100	1.35×10^{4}
Ce^{143}	2.10	1.36	100	2.10×10^{4}	0.5	100	2.10×10^{4}
[1] Rh^{103}	2.10	None	--	--	0.04	100	2.10×10^{4}
Ru^{103}	2.20	0.22	90	1.98×10^{4}	0.495	90	1.98×10^{4}
		0.11	10	2.2×10^{3}	0.610	10	2.2×10^{3}
Sr^{89}	2.4	1.5	100	2.4×10^{4}	None	--	--
[2] Y^{91}	2.7	1.54	100	2.7×10^{4}	None	--	--
Zr^{93}	2.8	0.4	100	2.8×10^{4}	0.71	100	2.8×10^{4}
Nd^{147}	4.5	0.4	40	1.80×10^{4}	0.58	40	1.8×10^{4}
		0.9	60	2.70×10^{4}			
Ce^{141}	5.4	0.41	70	3.78×10^{4}	0.141	70	3.78×10^{4}
		0.56	30	1.62×10^{4}			
Te^{132}	6.2	0.28	50	3.1×10^{4}	0.22	50	3.1×10^{4}
I^{132}	6.6	0.73	15	9.9×10^{3}	0.96	23	1.52×10^{4}
		0.90	20	1.32×10^{4}	0.53	24	1.58×10^{4}
		1.16	23	1.52×10^{4}	1.40	15	9.9×10^{3}
		1.53	24	1.58×10^{4}	0.78	18	1.19×10^{4}
		2.12	18	1.19×10^{4}	0.67	18	1.19×10^{4}
I^{131}	6.6	0.60	85	5.61×10^{4}	0.36	85	5.61×10^{4}
		0.32	15	0.99×10^{4}	0.64	15	9.9×10^{3}
Po^{143}	8.8	0.93	100	8.8×10^{4}	None	--	--

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Mo^{99}	9.0	0.45	15	1.35×10^4	0.78	15	1.35×10^4
		1.23	85	7.65×10^4	0.14	85	7.65×10^4
Ba^{140}	9.6	0.48	40	3.84×10^4	0.54	40	3.84×10^4
		1.02	60	5.76×10^4			
La^{140}	10.5	1.32	70	7.35×10^4	1.6	10	1.05×10^4
		1.67	20	2.10×10^4	0.49	20	2.10×10^4
		2.26	10	1.05×10^4	0.82	70	7.35×10^4

10 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
$_1$Rh^{103}	2.55	None	--	--	0.04	100	2.55×10^4
Ru^{103}	2.60	0.22	90	2.34×10^4	0.495	90	2.34×10^4
		0.11	10	2.6×10^3	0.610	10	2.6×10^3
Sr^{89}	2.90	1.5	100	2.9×10^4	None	--	--
$_2$Y^{91}	3.2	1.54	100	3.2×10^4	None	--	--
Zr^{95}	3.35	0.4	100	3.35×10^4	0.71	100	3.35×10^4
Nd^{147}	4.80	0.4	40	1.92×10^4	0.58	40	1.92×10^4
		0.9	60	2.88×10^4			
Te^{132}	5.10	0.28	50	2.55×10^4	0.22	50	2.55×10^4
I^{132}	5.30	0.73	15	7.95×10^3	0.96	23	1.22×10^4
		0.90	20	1.06×10^4	0.53	24	1.27×10^4
		1.16	23	1.22×10^4	1.40	15	7.95×10^3
		1.53	24	1.27×10^4	0.78	18	9.54×10^3
		2.12	18	9.54×10^3	0.67	18	9.54×10^3
Ce^{141}	6.3	0.41	70	4.41×10^4	0.141	70	4.41×10^4
		0.56	30	1.89×10^4			
Mo^{99}	6.8	0.45	15	1.02×10^4	0.78	15	1.02×10^4
		1.23	85	5.78×10^4	0.14	85	5.78×10^4
I^{131}	6.8	0.60	85	5.78×10^4	0.36	85	5.78×10^4
		0.32	15	1.02×10^4	0.64	15	1.02×10^4
Pr^{143}	10.00	0.93	100	1.0×10^5	None	--	--
Ba^{140}	10.70	0.48	40	4.28×10^4	0.54	40	4.28×10^4
		1.02	60	6.42×10^4			
La^{140}	12.00	1.32	70	8.4×10^4	1.6	10	1.2×10^4
		1.67	20	2.4×10^4	0.49	20	2.4×10^4
		2.26	10	1.2×10^4	0.82	70	8.4×10^4

30 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Ce^{144}	2.00	0.3	70	1.4×10^{4}	0.17	30	6.0×10^{3}
Pr^{144}	2.00	3.00	95	1.9×10^{4}	0.696	2.0	4.0×10^{2}
		2.30	2	4.0×10^{2}	2.2	2.1	4.2×10^{2}
		0.8	3	6.0×10^{2}	1.5	0.9	1.8×10^{2}
I^{131}	3.60	0.60	85	3.06×10^{4}	0.36	85	3.06×10^{4}
		0.32	15	5.4×10^{3}	0.64	15	5.4×10^{3}
Nd^{147}	4.10	0.4	40	1.64×10^{4}	0.58	40	1.64×10^{4}
		0.9	60	2.46×10^{4}			
Cb^{95} 2	4.20	0.146	100	4.2×10^{4}	0.76	100	4.2×10^{4}
Rh^{103} 1	5.5	None	--	--	0.04	100	5.5×10^{4}
Ru^{103}	5.7	0.2	100	5.7×10^{4}	0.24	50	2.85×10^{4}
Sr^{89}	6.70	1.50	100	6.7×10^{4}	None	--	--
2 Y^{91}	7.6	1.54	100	7.6×10^{4}	None	--	--
Zr^{95}	8.2	0.4	100	8.2×10^{4}	0.76	100	8.2×10^{4}
Ba^{140}	10.80	0.48	40	4.32×10^{4}	0.54	40	4.32×10^{4}
		1.02	60	6.48×10^{4}			
Pr^{143}	11.00	0.93	100	1.1×10^{5}	None	--	--
La^{140}	12.50	1.32	70	8.74×10^{4}	1.6	10	1.25×10^{4}
		1.67	20	2.5×10^{4}	0.49	20	2.5×10^{4}
		2.26	10	1.25×10^{4}	0.82	70	8.74×10^{4}
Ce^{141}	11.30	0.41	70	7.91×10^{4}	0.141	70	7.91×10^{4}
		0.56	30	3.39×10^{4}			

60 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Nd^{147}	1.4	0.4 0.9	40 60	5.6×10^3 8.4×10^3	0.58	40	5.6×10^3
I^{131}	1.00	0.60 0.32	85 15	8.5×10^3 1.5×10^3	0.36 0.64	85 15	8.5×10^3 1.5×10^3
Ce^{144}	4.00	0.3	70	2.8×10^4	0.17	30	1.2×10^4
Pr^{144}	4.00	3.0 2.3 0.8	95 2 3	3.80×10^4 8.0×10^2 1.2×10^3	0.696 2.2 1.5	2.0 2.1 0.9	8.0×10^2 8.0×10^2 3.6×10^2
Ba^{140}	5.10	0.48 1.02	40 60	2.04×10^4 3.06×10^4	0.54	40	2.64×10^4
La^{140}	5.70	1.32 1.67 2.26	70 20 10	3.99×10^4 1.14×10^4 5.7×10^3	1.6 0.49 0.82	10 20 70	5.7×10^3 1.14×10^4 3.99×10^4
Pr^{143}	6.10	0.93	100	6.10×10^4	None	--	--
${}_{1}Rh^{103}$	7.20	None	--	--	0.04	100	7.2×10^4
Ru^{103}	7.40	0.22 0.11	90 10	6.66×10^4 7.4×10^3	0.495 0.610	90 10	6.66×10^4 7.4×10^3
Sr^{89}	9.70	1.50	100	9.7×10^4	None	--	--
Ce^{141}	10.8	0.41 0.56	70 30	7.56×10^4 3.24×10^4	0.141	70	7.56×10^4
${}_{2}Y^{91}$	11.20	1.54	100	1.12×10^5	None	--	--
${}_{2}Cb^{95}$	11.80	0.146	100	1.18×10^5	0.76	100	1.18×10^5
Zr^{95}	12.8	0.4	100	1.28×10^5	0.76	100	1.28×10^5

120 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Pm^{147}	1.05	0.22	100	1.05×10^4	None	--	--
[1] Rh^{103}	6.20	None	--	--	0.04	100	6.2×10^4
Ce^{141}	6.30	0.41 0.56	70 30	4.41×10^4 1.89×10^4	0.141	70	4.41×10^4
Ru^{103}	6.40	0.22 0.11	90 10	5.76×10^4 6.4×10^3	0.495 0.610	90 10	5.76×10^4 6.4×10^3
Ce^{144}	7.90	0.3	70	5.53×10^4	0.17	30	2.37×10^4
Pr^{144}	7.90	3.0 2.3 0.8	95 2 3	7.5×10^4 1.58×10^3 2.37×10^3	0.696 2.2 1.5	2.0 2.1 0.9	1.58×10^3 1.66×10^3 7.1×10^2
Sr^{89}	10.3	1.50	100	1.03×10^5	None	--	--
[2] Y^{91}	12.7	1.54	100	1.27×10^5	None	--	--
Zr^{95}	15.3	0.4	100	1.53×10^5	0.71	100	1.53×10^5
[2] Cb^{95}	20.4	0.146	100	2.04×10^5	0.76	100	2.04×10^5

365 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
Cs^{137}	1.5	0.51 1.20	95 5	1.43×10^4 7.5×10^2	None	--	--
Ba^{137}	1.5	None	--	--	0.67	100	1.5×10^4
Sr^{90}	1.90	0.54	100	1.9×10^4	None	--	--
Y^{90}	1.90	2.2	100	1.9×10^4	None	--	--
Ru^{106}	2.45	0.04	100	2.45×10^4	None	--	--
Rh^{106}	2.45	3.55 2.30	82 18	2.01×10^4 4.4×10^3	1.25 0.73 0.51	1.0 17 17	2.45×10^2 4.17×10^3 4.17×10^3
Sr^{89}	2.65	1.50	100	2.65×10^4	None	--	--
$_2Y^{91}$	3.90	1.54	100	3.9×10^4	None	--	--
Pm^{147}	5.80	0.22	100	5.80×10^4	None	--	--
Zr^{95}	7.20	0.4	100	7.2×10^4	0.71	100	7.2×10^4
$_2Cb^{95}$	15.0	0.146	100	1.5×10^5	0.76	100	1.5×10^5
Ce^{144}	26.5	0.30	70	1.85×10^5	0.17	30	7.95×10^4
Pr^{144}	26.5	3.0 2.3 0.8	95 2 3	25.2×10^4 5.3×10^3 7.95×10^3	0.696 2.2 1.5	2.0 2.1 0.9	5.3×10^3 5.3×10^3 2.38×10^3

730 Days

Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
$_2Cb^{95}$	1.00	0.146	100	1.0×10^4	0.76	100	1.0×10^4
Ru^{106}	3.40	0.041	100	3.4×10^4	None	--	--
Rh^{106}	3.40	3.55	82	2.79×10^4	1.25	1.0	3.4×10^2
		2.30	18	6.12×10^3	0.73	17	5.78×10^3
					0.51	17	5.78×10^3
Cs^{137}	4.1	0.51	95	3.89×10^4	None	--	--
		1.20	5.0	2.05×10^3	--	--	--
Ba^{137}	4.1	None	--	--	0.67	100	4.1×10^4
Sr^{90}	5.2	0.54	100	5.2×10^4	None	--	--
Y^{90}	5.2	2.2	100	5.2×10^4	None	--	--
Pm^{147}	13.5	0.22	100	1.35×10^5	None	--	--
Ce^{144}	30.00	0.30	70	2.1×10^5	0.17	30	9×10^4
Pr^{144}	30.00	3.0	95	2.85×10^5	--	--	--
		2.3	2	6.0×10^3	0.696	2.	6.0×10^3
		0.8	3	9.0×10^3	2.2	2.1	6.3×10^3
					1.5	0.9	2.7×10^3

				3650 Days			
Isotopes	% Total Activity	β Energies	% of β Decay	β d/m	γ Energies	% of γ Decay	γ d/m
* Sm^{151}	2.5	0.075	100	2.5×10^4	0.020	100	2.5×10^4
Pm^{147}	15.8	0.22	100	1.58×10^5	None	--	--
Cs^{137}	18.3	0.51	95	1.74×10^5	None	--	--
		1.20	5	9.00×10^3	--	--	--
Ba^{137}	18.3	None	--	--	0.67	100	1.83×10^5
Sr^{90}	22.0	0.54	100	2.2×10^5	None	--	--
Y^{93}	22.0	2.2	100	2.2×10^5	None	--	--

* Half life listed as 20 years by Hunter & Ballou later data report $t_{1/2}$ = 100 years

APPENDIX C

Isotope	d/m		λ (min^{-1})		Atoms	Factor	Disintegrations
Ru^{103}	3.2	10^4	1.14	10^{-5}	2.81×10^9	3	8.4×10^9
Rh^{103}	6.2	10^4	1.24	10^{-2}	5.0×10^6	1	0×10^9
Ce^{141}	4.41	10^4	1.72	10^{-5}	2.6×10^9	1	2.6×10^9
Ce^{144}	2.37	10^4	1.75	10^{-6}	1.36×10^{10}	1-1/6	15.8×10^9
Pr^{144}	3.95	10^3	3.96	10^{-2}	1.0×10^5	1	0×10^9
Zr^{95}	1.53	10^5	7.4	10^{-6}	2.07×10^{10}	2	41.4×10^9
$_2Cb^{95}$	2.04	10^5	1.37	10^{-5}	1.49×10^{10}	1	14.9×10^9
Cs^{137}	(2.5	10^3)*	3.57	10^{-8}	7.00×10^{10}	1	70.0×10^9
Ba^{137}	2.5	10^3	2.77	10^{-1}	9×10^3	1	0×10^9
Sm^{151}	5	10^2	6.6	10^{-8}	7.5×10^9	1	7.5×10^9
Ru^{106}	(6	10^3)*	1.32	10^{-6}	4.6×10^9	0.35	1.6×10^9
Rh^{106}	2.1	10^3	1.39	—	1.5×10^3	1	0×10^9
						Total:	162.2×10^9

The "Factor" in column 5 takes into account the gamma disintegrations of the daughter product.

* Cs^{137} and Ru^{106} are beta emitters, but their daughters show gamma emission.