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AN APPROACH TO A GENERAL METHOD OF COMPUTING DOSES AND EFFECTS FROM FALL-OUT

This document was prepared by the Secretariat of the United Nations in collaboration with a group of experts of the United Nations Scientific Committee on the Effects of Atomic Radiation as a working paper. It was completed just before the fifth session (9 - 13 June 1958) of the Committee. The Committee has not had sufficient time to study and eventually to accept this work, which was considered to be of substantial scientific interest; it has decided to make this paper available because it will be useful to scientists engaged in calculations of gonod or bone marrow doses and their biological effects.

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I. INTRODUCTION

As this paper was prepared as a working paper in connexion with the preparation of the comprehensive report of the United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations document A/3838, references to Annexes D, G and H in the following text always refer to the annexes of that document.

1. The purpose the calculations in this paper is to assess the possible total incidence of deleterious biological effects of fall-out from nuclear test explosions. This is a different mode of assessment from the one used in earlier approaches (e.g. Annex D), where the incidence in the most highly exposed generation has been computed. A more general type of calculation is here presented.

2. The estimate of doses from fall-out, and even more the evaluation of the biological effects, is an extremely difficult undertaking the results of which must be treated with great reserve, since numerous assumptions have to be made, the validity of which cannot yet be verified.

3. Where the biological effect on a population, expressed as the number of specified incidents of an injury, is the object of the computation, one must consider the time-lag caused by the long retention of radioactive material in the stratosphere. There is also a prolonged period in which uptake of radioactivity and subsequent radiation exposure occurs. Although a third time-lag, namely that between the exposure and the incidence of an injury is common to all sources, most sources other than fall-out produce or initiate biological effects to a degree that can be measured by the extent of the radiation exposure at any time. In the case of fall-out, however, exposure at a certain time already implies subsequent exposure at other times. The total biological consequences of test explosions carried out up to a given date must therefore be evaluated by computing the future inevitable dose, as well as the present and past exposures.

4. The calculations below have been made on the basis of the following two assumptions relating radiation dose with possible biological effect:

(a) There is no threshold of the relevant dose, and the dose-effect relation is linear, and

(b) There exists a threshold of the relevant dose.

(a) Case of non-threshold, linear dose-effect relation

5. The genetically relevant dose will be calculated as the infinite time integral of the gonad dose rate, assuming that all individuals will be exposed to the same dose rate irrespective of age and sex.

6. The dose relevant to the estimate of the possible radiation-induced occurrence of leukemia, caused by a particular time distribution of the environmental contamination, can be calculated as the infinite time integral of the per capita mean bone marrow dose rate, taking into account the influence of age. As will be seen in the following, the same result can be derived by a more direct method of calculation, which has been preferred here.

7. The above doses, multiplied by the number of population and an appropriate constant, will give the total number of affected individuals in the population for all time during and subsequent to the exposure. All these calculations necessitate a number of assumptions which will be stated in detail in the following text.

8. No scientific prediction of the future practice of weapon tests is possible. The Committee has nevertheless considered it informative to study what damage continuation of the test practice of the past few years may bring about. As long as linear dose-effect relation is assumed with no threshold, each year of testing must result in the same ultimate total number of injuries, if the rate of injection of long-lived fission products into the stratosphere is the same. It is therefore appropriate to compare radiation doses and, where possible, the biological effect for one year of each practice that will, whether at the time or subsequently, give rise to exposure.

9. For the total effect is is irrelevant when the exposure occurs, and only the total relevant dose need be known. A year of each practice should therefore be considered as related to a total dose-commitment rather than to some actual exposure over a given period.

(b) Case of threshold assumption

10. In the threshold case, on the other hand, the comparison of actual exposures is necessary to consider whether the sum of the contributions exceeds the threshold at any time. For that reason, estimated exposures over appropriate periods of time (70 years for the marrow exposure) have been made. (As it may also be of individual interest to know when the mutational damage will enter the population at the maximum rate, 30-year integrals of the gonad dose have been calculated).

Assumptions made for the purpose of calculations

11. The uncertainty and complexity of the calculations may be exemplified by the computation of the relevant bone marrow dose due to Sr^{90} from stratospheric fall-out, which involves the following steps:

1. Assumption on rate of injection of Sr^{90} into the stratosphere.
2. Assumption of mechanism and numerical expression for depletion of the stratospheric reservoir.
3. Calculation of the rate of Sr^{90} fall-out.
4. Assumptions regarding the geographical distribution of fall-out and estimate of a population-weighted average.
5. Calculation of the accumulated fall-out deposit.
6. Assumption of future influence of weathering.
7. Numerical assumptions concerning food chain transmission of Sr^{90} and calculation of the contamination of diet.
8. Numerical assumptions concerning uptake and retention of Sr^{90}.
9. Calculation of accumulated Sr^{90} concentration in bone as a function of calendar date and date of birth.
10. Numerical assumption connecting Sr^{90} concentration in bone with marrow dose, including assumption on the relative location of Sr^{90} with relation to the location of active marrow. Assumptions on the size distribution of the marrow cavities must be made.
11. Assumption regarding the appropriate dose for estimates of a possible induction of leukemia.

12. Assumption on dose-effect relationship and possible weighting factors for age, marrow size (mass of active marrow) or other parameters of biological significance.
13. Calculation of the appropriate dose rate.
14. Calculation of the appropriate individual dose.
15. Calculation of the per capita dose due to a certain contamination of the environment.
16. Integration of the per capita dose over all environmental contributions due to a certain injection.

II. THE FALL-OUT FUNCTIONS

Mechanism of depletion of the stratospheric reservoir

12. In Annex D, the assumption has been made that the rate of depletion of radioactive material from the stratosphere at any time is proportional to the quantity stored there. This assumption can be formulated as

$$\overline{F}_r(t) = k \cdot \overline{Q}(t) \qquad (1)$$

where $\overline{F}_r(t)$ = fall-out rate per unit area of the surface of the earth ($mc/km^2 \cdot year$).

k = time constant of depletion ($year^{-1}$).

$\overline{Q}(t)$ = Sr^{90} (or Cs^{137}) content of the stratosphere; expressed per unit area of the surface of the earth (mc/km^2).

The value of k has been assumed to be 0.1/yr. Values ranging from 0.07/year to 0.2/year have been considered possible by various authors.[1,2,3]

13. In addition to the exponential retention implied by the above assumption, the following two general equations for the material balance must be used for the evaluation of the depletion.

$$\frac{d\overline{Q}}{dt} = n - \lambda\overline{Q} - \overline{F}_r(t) \qquad (2)$$

$$\frac{d\overline{F}_d(t)}{dt} = \overline{F}_r(t) - \lambda\overline{F}_d(t) \qquad (3)$$

where n = rate of injection of Sr^{90} (or Cs^{137}) into the stratosphere, expressed per unit area of the surface of the earth ($mc/km^2 \cdot year$).

$\overline{F}_d(t)$ = accumulated deposit of Sr^{90} (or Cs^{137}) per unit area (mc/km^2).

λ = 0.025/year = disintegration constant of Sr^{90} (or Cs^{137}).

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Geographical factors

14. $\overline{F}_r(t)$, $\overline{F}_d(t)$ and n in the equations are not local values but averaged over the whole surface of the earth. These geographical averages are not relevant for estimates of the biological effects on a specific population (i) or on the whole population of the earth. Although not used in these calculations, appropriate local values of $F_r^{(i)}(t)$ and $F_d^{(i)}(t)$ might be derived by help of a geographic factor $G_i(t)$, such that

$$F_r^{(i)}(t) = G_i(t) \cdot \overline{F}_r(t) \qquad (4)$$

$$F_d^{(i)}(t) = G_i(t) \cdot \overline{F}_d(t) \qquad (5)$$

The geographical factor $G_i(t)$ is given as a function of latitude in Annex D.

15. A value $\overline{G}(t)$ appropriate for the whole population of the earth can be derived by averaging through summation over all population N_i. The present value has been calculated as

$$\overline{G}(0) = \frac{\sum G_i(0) \cdot N_i}{\sum N_i} \approx 2 \qquad (6)$$

16. It is possible that the local variation of $G_i(t)$ will change after the cessation of injection, and that $\overline{G}(t)$ may approach unity. However, as the geographical variation of the fall-out rate in the future cannot at present be predicted, it has been assumed that at any time

$$\overline{G}(t) = \overline{G}(0) \approx 2 \qquad (7)$$

General expressions of the fall-out functions

17. In the case that the injection rate is constant, it is possible to integrate the equations (2) and (3), the general solution for the populated weighted average being

$$F_r(t) = \overline{G}(t) \cdot \overline{F}_r(0) \cdot e^{-\lambda t} + \overline{G}(t) \cdot \frac{kn}{\lambda}(1 - e^{-\lambda t}) \qquad (8)$$

$$F_d(t) = \bar{G}(t)\,\bar{F}_d(0)\cdot e^{-\lambda t} + \bar{G}(t)\cdot\frac{\bar{F}_r(0)}{k}\,(e^{-\lambda t} - e^{-\Lambda t}) + \bar{G}(t)\cdot\frac{n}{\lambda}\,\left(\frac{k}{\Lambda} + \frac{\lambda}{\Lambda}\,e^{-\Lambda t} - e^{-\lambda t}\right) \qquad (9)$$

where $\Lambda = k + \lambda$.

18. In the following $F_r(t)$ and $F_d(t)$ will denote the population weighted fall-out functions as derived with $\bar{G}(t) = 2$. It will be assumed that $t = 0$ at the end of 1958. For that time the following values of fall-out rate and deposit have been used (see discussion in Annex D)

$$\bar{F}_r(0) = 1.5 \text{ mc/km}^2 \cdot \text{year}$$

$$\bar{F}_d(0) = 5.0 \text{ mc/km}^2$$

Assumptions with regard to the continuation of weapon tests

19. In considering pattern of testing two cases have been discussed in Annex D, namely

Assumption (a): The fall-out rate will remain constant and equal to $\bar{F}_r(0)$. In the case of the condition implied by Equation (1), this will mean a constant stratospheric content (mainly due to large initial injections), maintained by a compensating constant injection rate that must satisfy the relation

$$n_a = \bar{F}_r(0)\cdot\frac{\Lambda}{k} \qquad (10)$$

Assumption (b): The injection rate will remain at a value equal to the mean value for the five years 1954 to 1958 inclusive. This gives

$$n_b = \frac{\lambda}{1 - e^{-5\lambda}}\,\left(\bar{F}_d(0) + \frac{\bar{F}_r(0)}{k}\right) \qquad (11)$$

20. With the values assumed for k, λ, $\bar{F}_r(0)$ and $\bar{F}_d(0)$, the two injection rates will be

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$$n_a = 1.875 \text{ mc/km}^2 \cdot \text{year}$$

$$n_b = 4.25 \text{ kc/km}^2 \cdot \text{year}$$

Particular expressions for specified intervals of time

21. Full dose calculations require complete information on the fall-out functions for any time. It is necessary to consider separately the following three intervals:

(A) Period before end of 1958,

(B) Period between end of 1958 and the time of cessation of injection,

(C) Period after time of cessation.

(A) Period before end of 1958

22. Neither of the assumptions (a) and (b) describes the actual fall-out during the period before the end of 1958. To simplify the calculations, the fall-out before 1954 will be neglected, and a linear increase of the fall-out rate will be assumed after an initial large injection that year. To fit the values of rate and deposit assumed for 1958, the past fall-out rate will be approximated by the assumption that $\overline{F}_r(t)$ rose linearly from 0.5 mc/km^2 · year in early 1954 to 1.5 1.5 mc/km · year at the end of 1958. This implies that $\overline{F}_d(t)$ did not rise linearly but according to a second power expression from 0 in early 1954 to 5 mc/km^2 at the end of 1958, i.e.

$$F_r(t) = \overline{G} \cdot \overline{F}_r(t) = \overline{G} \cdot (1.5 + 0.2\ t) \qquad (12)$$

$$F_d(t) = \overline{G} \cdot \overline{F}_d(t) = \overline{G} \cdot (5 + 1.5\ t + 0.1\ t^2) \qquad (13)$$

($t < 0$, $t = 0$ at the end of 1958)

As the corresponding contribution to the dose is small compared with the contribution from future fall-out, this approximation is quite satisfactory for the dose computations.

(B) Period between end of 1958 and the time of cessation of injection

23. For the period between the end of 1958 and the time of cessation of injection, the equations (8) and (9) are valid. The calculation will be carried out for the two assumptions (a) and (b) assuming the value of n_a and n_b given above. The equations can be rearranged to read

$$F_r(t) = \overline{G} \cdot \frac{kn}{\Lambda} - \overline{G} \cdot \left(\frac{kn}{\Lambda} - \overline{F}_r(0)\right) \cdot e^{-\Lambda t} \qquad (14)$$

$$F_d(t) = \overline{G} \cdot \frac{1}{\lambda} \cdot \frac{kn}{\Lambda} + \overline{G} \cdot \left(\frac{n}{\Lambda} - \frac{\overline{F}_r(0)}{k}\right) \cdot e^{-\Lambda t} - \overline{G} \cdot \left(\frac{n}{\lambda} - \frac{\overline{F}_r(0)}{k} - \overline{F}_d(0)\right) \cdot e^{-\lambda t} \qquad (15)$$

(C) Period after cessation of injection

24. If all injection is ceased at a time t = T, the fall-out functions will for for all subsequent time be

$$F_r(t) = \overline{G} \cdot \overline{F}_r(T) \cdot e^{-\Lambda(t - T)} \qquad (16)$$

$$F_d(t) = \overline{G} \cdot \left(\overline{F}_d(T) + \frac{1}{k} \cdot \overline{F}_r(T)\right) \cdot e^{-\lambda(t - T)} - \overline{G} \cdot \frac{1}{k} \cdot \overline{F}_r(T) \cdot e^{-\Lambda(t - T)} \qquad (17)$$

Summary

25. The following values of the constants have been used in the calculations

$k = 0.1$ / year

$\lambda = 0.025$ / year (for both Sr^{90} and Cs^{137})

$\Lambda = 0.125$ / year

$n_a = 1.875$ mc/km^2 · year

$n_b = 4.25$ mc/km^2 · year

$\overline{G} = 2$

$\overline{F}_r(0) = 1.5$ mc/km^2 · year

$\overline{F}_d(0) = 5$ mc/km^2

26. The fall-out functions (giving the magnitudes in the same units as $\overline{F}_r(0)$ and $\overline{F}_d(0)$ above and assuming the time is measured in years) will accordingly be simplified to

(A) $t<0$

$$F_r(t) = 3 + 0.4\,t \tag{18}$$

$$F_d(t) = 10 + 3\,t + 0.2\,t^2 \tag{19}$$

(B) $0<t<T$

Assumption (a):

$$F_r(t) = 3 \tag{20}$$

$$F_d(t) = 120 - 110 \cdot e^{-0.025\,t} \tag{21}$$

Assumption (b):

$$F_r(t) = 6.8 - 3.8 \cdot e^{-0.125\,t} \tag{22}$$

$$F_d(t) = 272 + 38 \cdot e^{-0.125\,t} - 300 \cdot e^{-0.025\,t} \tag{23}$$

(C) $t>T$ Here the equations (16) and (17) will be used for the cases T = 0, 10, 20 and 30 under both assumptions (a) and (b). In all cases, the expressions are of the type:

$$F_r(t) = \text{const.}\ e^{-\lambda(t - T)} = s_1(T) \cdot e^{-0.125\,t} \tag{24}$$

$$F_d(t) = s_2(T) \cdot e^{-0.025\,t} - s_3(T) \cdot e^{-0.125\,t}$$

where the constants $s_1(T)$, $s_2(T)$ and $s_3(T)$ have the following values

/...

	case	$s_1(T)$	$s_2(T)$	$s_3(T)$
Assumption (a)	T = 0	3.000	40.00	30.00
	10	10.47	82.60	104.7
	20	36.55	137.3	365.5
	30	127.6	207.6	1276
Assumption (b)	T = 0	3.000	40.00	30.00
	10	19.93	136.6	199.3
	20	79.04	260.6	790.4
	30	285.4	419.8	2854

27. Figures 1 and 2 show the functions $F_r(t)$ and $F_d(t)$ respectively.

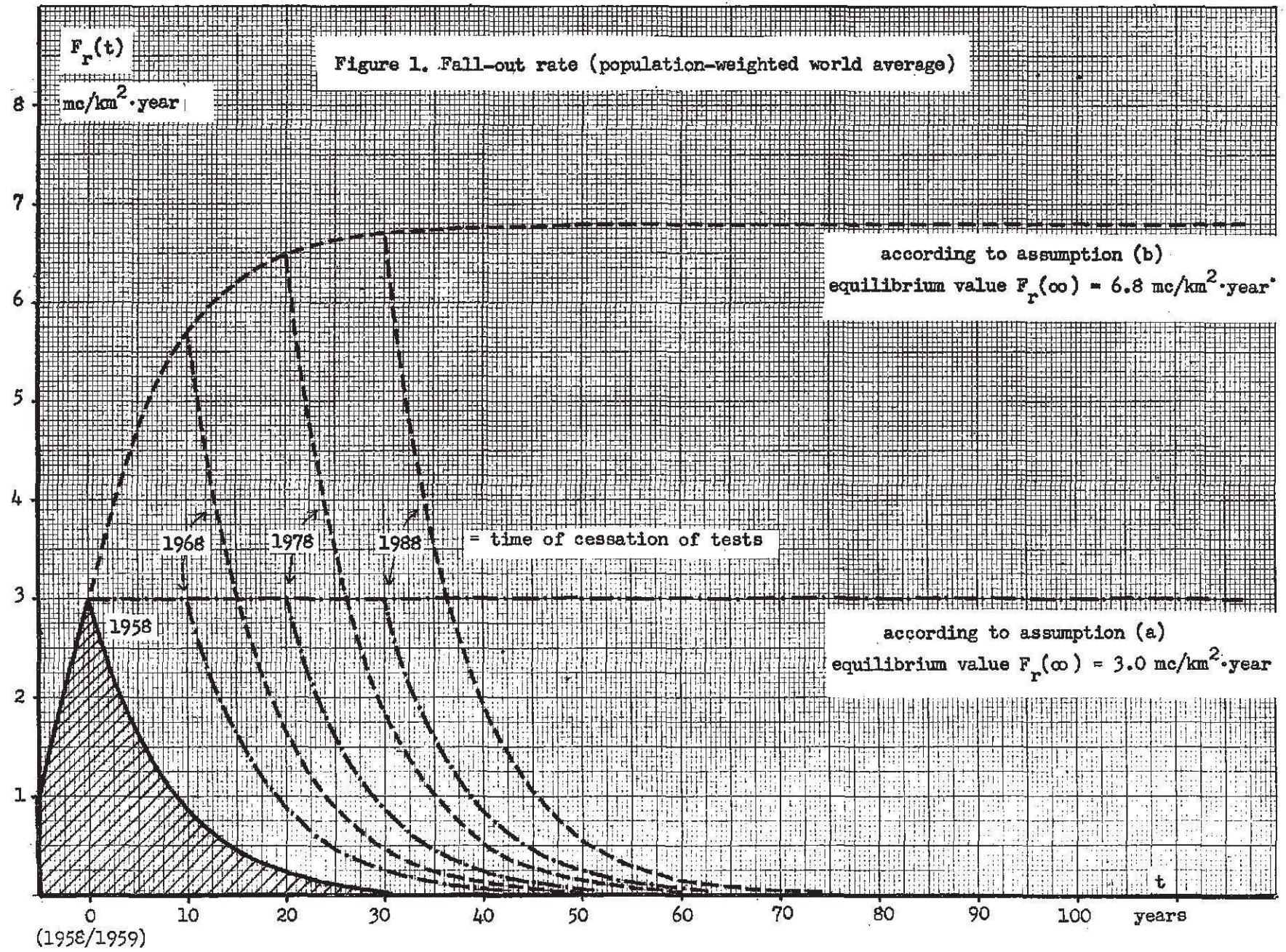
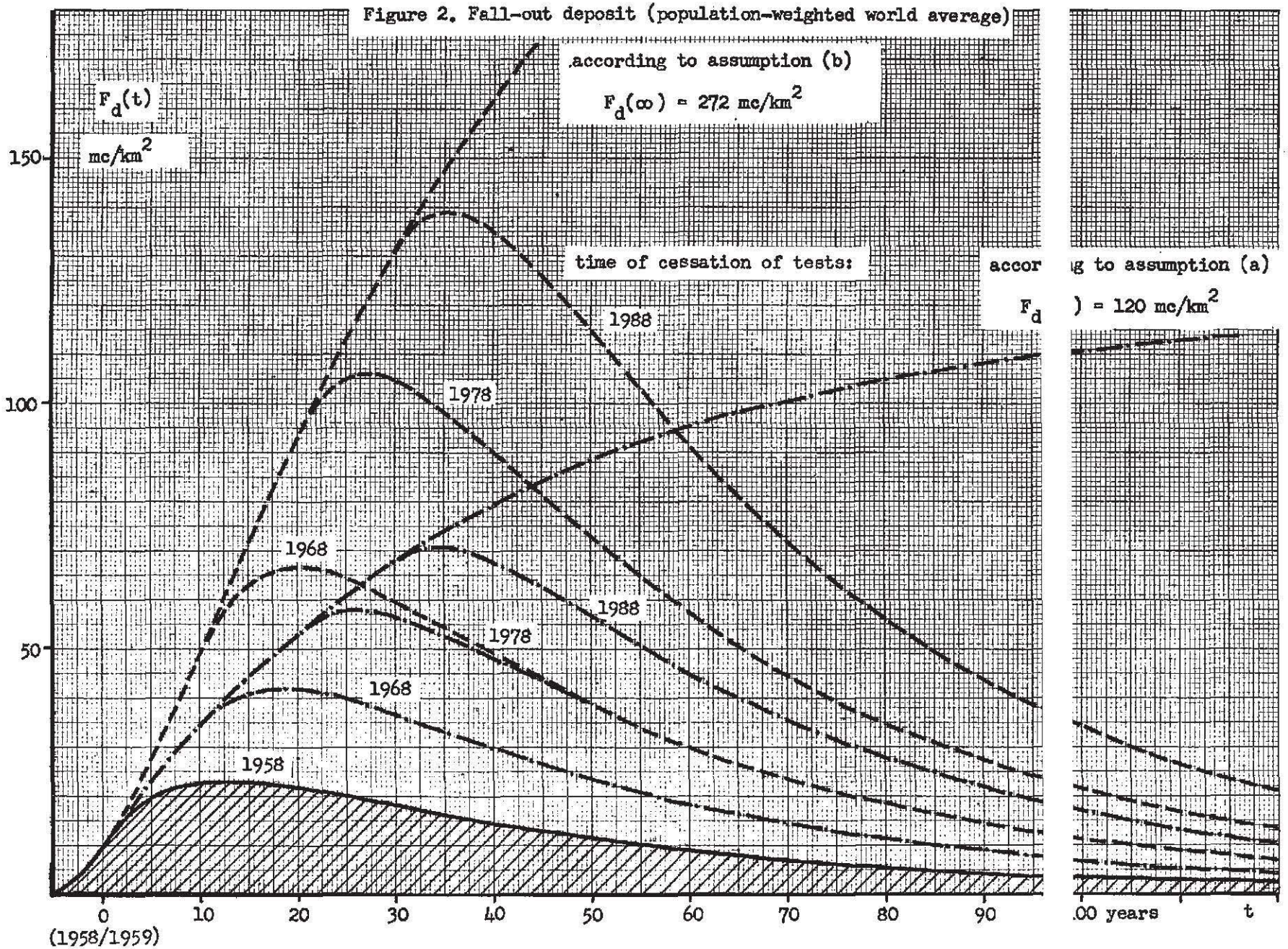


Figure 1. Fall-out rate (population-weighted world average)
$F_r(t)$
mc/km^2·year
8
7
6
5
4
3
2
1
according to assumption (b)
equilibrium value $F_r(\infty)$ = 6.8 mc/km^2·year
1968
1978
1988
= time of cessation of tests
1958
according to assumption (a)
equilibrium value $F_r(\infty)$ = 3.0 mc/km^2·year
t
0
10
20
30
40
50
60
70
80
90
100
years
(1958/1959)

Figure 2. Fall-out deposit (population-weighted world average)



III. GONAD EXPOSURE

Dose-effect relationship

28. The genetic effect of exposure from fall-out will be estimated on the assumption that the dose-effect relation is linear without threshold, and that all gonad dose contributions throughout the reproductive years are additive.

29. For the following calculations a model population (of constant size P) has been considered, where the age of breeding is 30 and the age of death 70 years for all members.*

30. The number of individuals affected subsequent to a certain gonad exposure will be estimated as the product of the population involved (which will be assumed to be constant), the appropriate dose and a dose-effect constant. The appropriate dose is the mean gonad dose to the reproductive fraction of the population. A dose increment δD will result in δN individuals affected in the future, computed as

$$\delta N = K_g \cdot P \cdot \delta D \qquad (26)$$

31. The genetic dose-effect constant K_g can be derived from estimates of the representative doubling dose $\overline{D}_2$ and the current fraction (f) of adversely affected births (see Annex H). In genetic equilibrium the doubling dose, if received by every individual from conception to age 30, will give rise to fB affected births per year where B is the birth-rate. As B is approximated by P/70, the relation between rate of introducing affected individuals and the rate of population exposure will be

$$\frac{dN}{dt} = \frac{3}{7} \cdot f \cdot P \cdot \frac{1}{\overline{D}_2} \cdot \frac{dD}{dt} \qquad (27)$$

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* In the following calculations the ratio of the breeding to the total population appears. For the model population assumed, this ratio is 30/70. In the general case the ratio is w/W (with the symbols used in Annex C) for constant populations, such as we may expect for the distant future. For actual populations that are today already relatively constant ("old" in the demographic sense), the ratio does not differ appreciably from 3/7, as can be seen from the data on child expectancy presented in Table I. Annex C.

Hence, in the above model population, not only in genetic equilibrium but as a result of any dose increment δD, the total subsequent number of affected individuals will be

$$\delta N = \frac{3}{7} \cdot f \cdot P \cdot \frac{1}{\overline{D}_2} \cdot \delta D \qquad (28)$$

and, therefore, the constant for the model population is

$$K_g = \frac{3}{7} \cdot f \cdot \frac{1}{\overline{D}_2} \ \text{rem}^{-1} \qquad (29)$$

32. In the case of stratospheric fall-out, the gonad exposure will be extended over many decades even if the injection is ceased now. Each year of injection will give rise to an extended exposure, i.e. will imply a certain dose commitment. For calculation of the total number of genetically affected individuals over subsequent years (N_g) the appropriate dose related to any pattern of injection is the infinite time integral of the mean gonad dose rate for all individuals of reproductive age. If this dose is denoted D_∞

$$N_g = K_g \cdot P \cdot D_\infty \qquad (30)$$

provided that the population remains constant.

33. If the fraction of annual births affected as a result of spontaneous mutation is taken to be in the range

$$f = 1 - 4\% \qquad \text{(Annex H)}$$

and the doubling dose is taken to be in the range

$$\overline{D}_2 = 10 - 100 \text{ rem},$$

then the value of the genetic dose-effect constant lies in the range

$$K_g = 43 - 1{,}710 \text{ rem}^{-1} \text{ per million}$$

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Gonad exposure from stratospheric fall-out

34. Both stratospheric and tropospheric fall-out contribute to the gonad exposure. As the tropospheric contribution is directly proportional to the rate of tropospheric injection, it can be considered as a constant annual contribution over the time during which this injection is maintained constant. This will be discussed in a later section. The stratospheric fall-out that contributes to the gonad exposure is assumed to be mainly Cs^{137}. The fall-out functions derived in part II of this paper can, therefore, be used as the basis for the dose computation. The gonad dose from Cs^{137} will result from both external and internal exposure.

External contribution

35. The following expression can be derived for the gonad dose rate when the source is a deposit on an infinite plan

$$\frac{dD}{dt} = k \cdot S \cdot B \cdot F_d(t) \text{ mrem/year} \quad (31)$$

where k = dose rate from primary radiation per mc/km^2 = 0.08 mrem/year

S = body shielding factor ≈ 0.6

B = build up factor = ratio total/primary radiation dose rate ≈ 2

$F_d(t)$ = deposit of Cs^{137} mc/km^2 assumed equal to $F_d(t)$ for Sr^{90}.

36. The above dose rate must be corrected by a factor for the effect of weathering and also by a factor for the effect of shielding by buildings and irregularities of the ground in the practical case. For the combined correction, factors between 3 and 21 have been suggested [4-7]; a factor of 10 will be assumed here. It must be emphasized that the uncertainty introduced by this factor may be greater than the spread implied by the suggested values.

37. From the above assumptions, the external contribution to the gonad dose rate will be derived as

$$\left(\frac{dD}{dt}\right)_e = g_e \cdot F_d(t) = 0.01 \cdot F_d(t) \text{ mrem/year} \quad (32)$$

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Internal contribution

38. Cs^{137} is taken up and excreted fairly rapidly by the body, but is poorly taken up from soil by plants. Therefore, both the contamination of food sources and the concentration in the human body have been assumed to be proportional to the fall-out rate, i.e.

$$\left(\frac{dD}{dt}\right)_i = g_i \cdot F_r(t) \qquad (33)$$

39. Experimental data on the body burden of Cs^{137} indicate that the average gonad dose rate amounted to 1 mrem/year in the United Kingdom and the United States during 1956 and 1957.[8,9] As the average fall-out rate over the two countries was about 3 mc/km^2.year (Fig. 2, Annex D) during these years, it will be assumed that $g_i = 0.3$ mrem/year per mc/km^2.year.

Formulas for dose-rate in the gonads

40. From the above assumptions it follows that the gonad dose rate can be written

$$\frac{dD}{dt} = g_i \cdot F_r(t) + g_e \cdot F_d(t) \qquad (34)$$

where the constants have been taken to be : $g_i = 0.3$ mrem/year per mc/km^2 . year and $g_e = 0.01$ mrem/year per mc/km^2. As the functions $F_r(t)$ and $F_d(t)$ representing population weighted averages are used, the dose-rate will be applicable for computation of the appropriate value of D_∞ for the whole population of the earth.

41. With the assumed values of the constants g_i and g_e the following expressions for the dose-rate have been derived (dose-rate in mrem/year, time in years).

(A) $t < 0$

$$\frac{dD}{dt} = 1.00 + 0.15\,t + 0.002\,t^2 \qquad (35)$$

(B) $0 < t < T$

Assumption (a) :

$$\frac{dD}{dt} = 2.1 - 1.1 \cdot e^{-0.025\,t} \qquad (36)$$

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Assumption (b) :

$$\frac{dD}{dt} = 4.76 - 0.76 \cdot e^{-0.125\,t} - 3.00 \cdot e^{-0.025\,t} \qquad (37)$$

(C) $t > T$

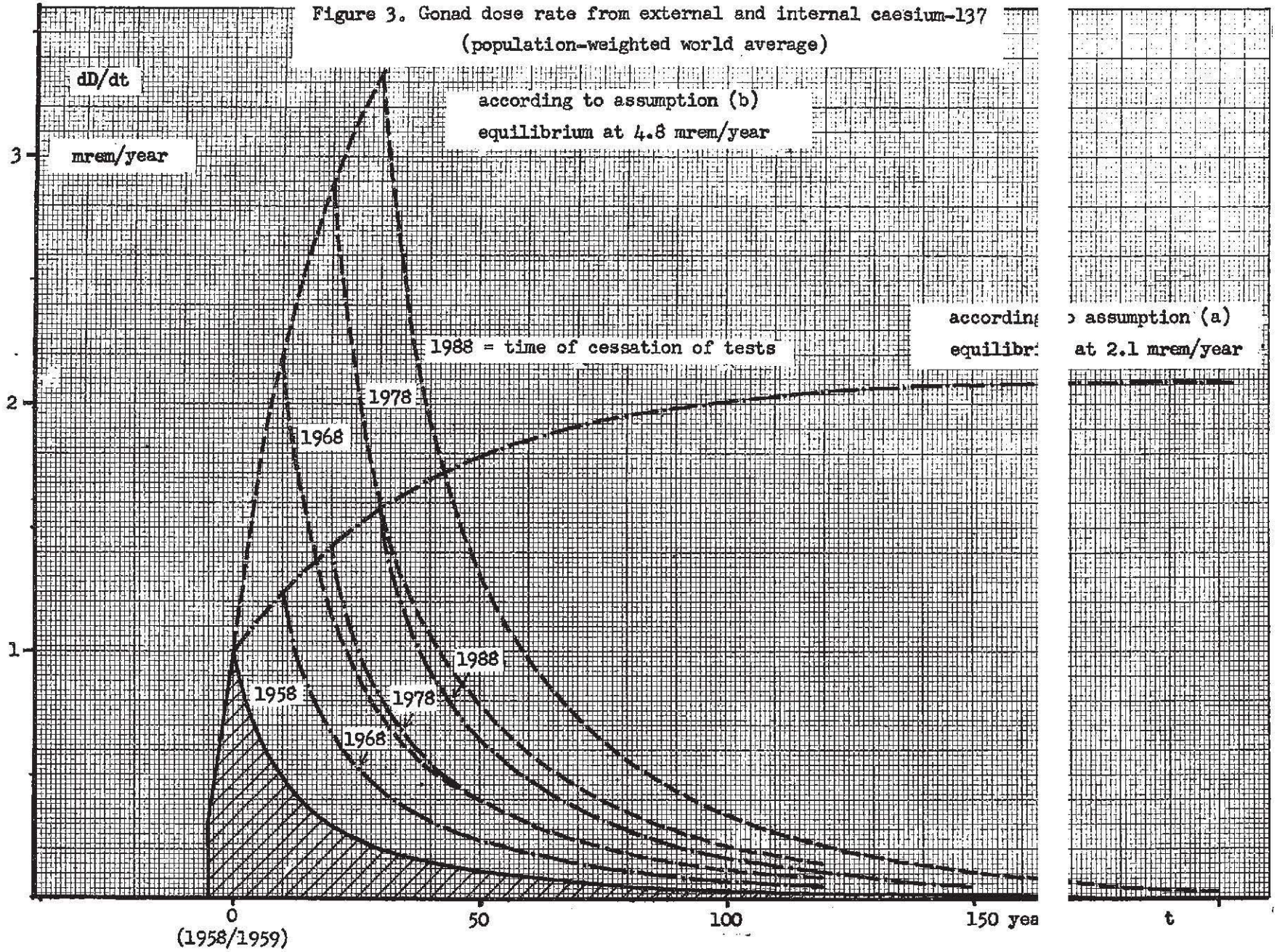
$$\frac{dD}{dt} = c_1(T) \cdot e^{-0.125\,t} + c_2(T) \cdot e^{-0.025\,t} \qquad (38)$$

where the constants $c_1(T)$ and $c_2(T)$ have the following values

	case	$c_1(T)$	$c_2(T)$
Assumption (a)	T = 0	0.6000	0.4000
	10	2.094	0.8260
	20	7.310	1.373
	30	25.52	2.076
Assumption (b)	T = 0	0.6000	0.4000
	10	3.986	1.366
	20	15.81	2.606
	30	57.08	4.198

42. Figure 3 gives curves showing the variation of gonad dose rate with time.

Figure 3. Gonad dose rate from external and internal caesium-137
(population-weighted world average)



Infinite time integral of gonad dose rate

43. The infinite time integral of the gonad dose rate has been calculated as the sum of the dose contributions D_A $(t<0)$, D_B $(0<t<T)$, and D_C $(t>T)$. The following table gives the contributions in mrem:

Table I

Infinite time integral of gonad dose rate (mrem)

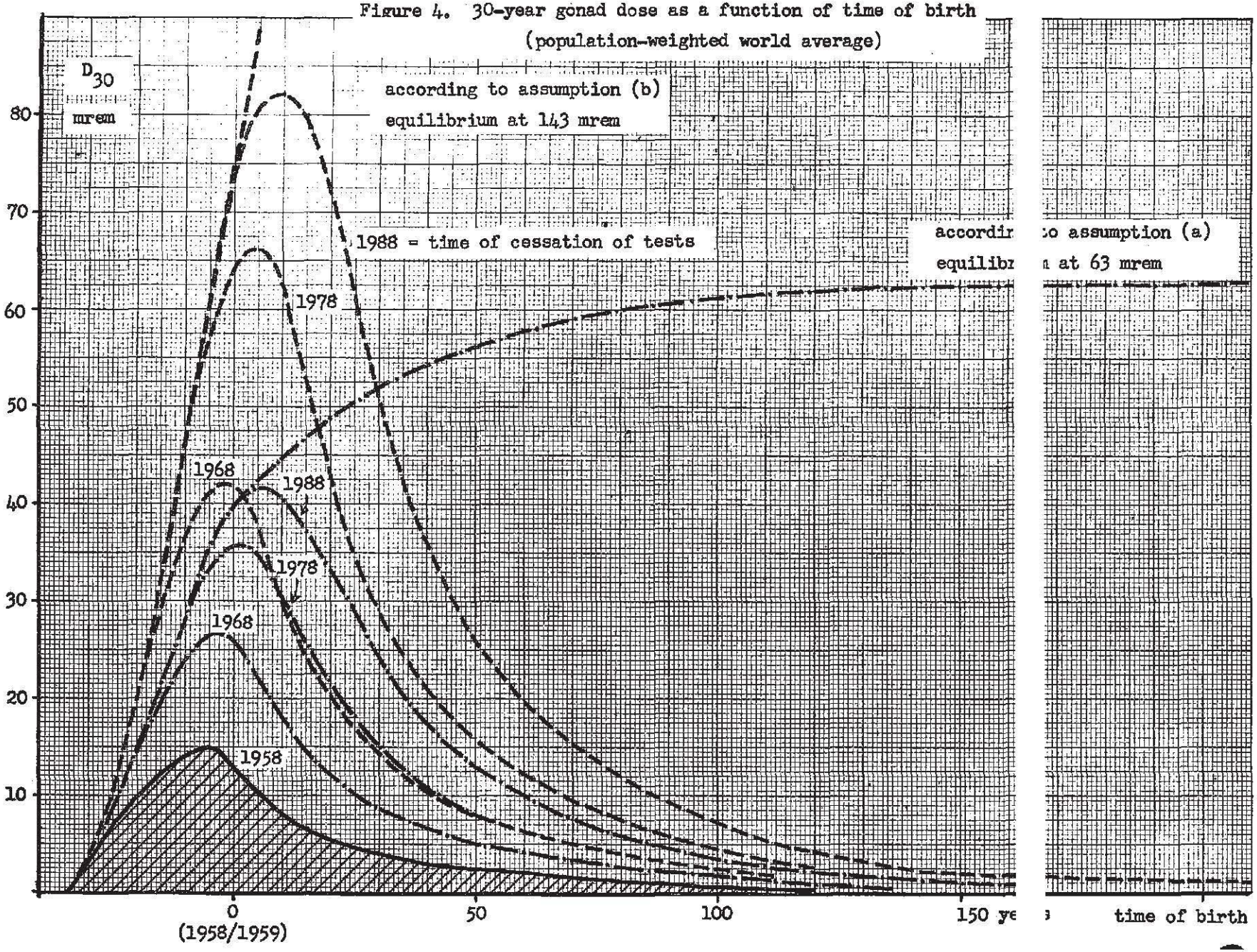
	Assumption (a)				Assumption (b)			
T =	0	10	20	30	0	10	20	30
D_A	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
D_B	0.0	11.3	24.7	39.8	0.0	16.7	42.4	73.5
D_C	20.8	30.5	38.1	44.0	20.8	51.7	73.6	90.1
Total	24.0	45.0	66.0	87.0	24.0	71.6	119.2	166.8
Diff.		21.0	21.0	21.0		47.6	47.6	47.6

44. Table I shows that each year of injection implies a dose commitment of 2.1 mrem on assumption (a) and 4.8 mrem on assumption (b). These figures can also be derived from equations (36) and (37) as equilibrium values.

30-year integrals of gonad dose rate

45. As it may be of individual interest to know when the mutational damage will enter the population at the maximum rate, 30-year integrals D_{30} of the gonad dose have been calculated. The variation of D_{30} with time of birth is shown in Figure 4.

Figure 4. 30-year gonad dose as a function of time of birth
(population-weighted world average)



46. Maximum values of D_{30} can be derived from Figure 4. The maximum values in the case where the injection is continued long enough to permit the equilibrium to be reached are 2.1 x 30 = 63 on assumption (a), and 4.76 x 30 = 143 on assumption (b). The maximum values of D_{30} are given in Table II.

Table II

Maximum values of D_{30}

	Tests ceased at end of	Assumption (a)		Assumption (b)	
		D_{30} (mrem)	% of equilibrium	D_{30} (mrem)	% of equilibrium
T = 0	1958	15	24	15	10
10	1968	27	43	42	29
20	1978	36	57	66	46
30	1988	42	67	82	57
∞	-	63	100	143	100

Contribution from tropospheric fall-out

47. Although the mechanism for depletion of the stratospheric reservoir of radioactive fission products is not known, the future fall-out has been estimated in the preceding paragraphs, assuming an exponential retention. As it is likely that the time constant is smaller than mean radioactive life of the most important isotope, Cs^{137}, this assumption will not critically affect the estimate of the infinite time integral of the gonad dose rate. As the maximum 30-year gonad dose will be received by individuals born during the decade 1950-1960, this estimate is also fairly reliable whatever the actual mechanism of depletion may be.

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48. In the case of tropospheric fall-out, on the other hand, the assumption on the fall-out mechanism will critically affect the estimate, since the type of isotopes deposited will depend on the time constants involved. As the computation of genetic effects on the linear dose-effect non-threshold assumption must be based upon a population-weighted average for the whole of the earth, certain geographical variations must be assumed. As the tropospheric fall-out deposit in equilibrium is proportional to the tropospheric injection rate, estimates of future deposit must be based upon assumptions on this rate.

49. It may be assumed that the presently observed level of tropospheric fall-out deposit represents an equilibrium of the most significant isotopes. A continuation of the present pattern of testing will therefore be expected to maintain the present tropospheric fall-out deposit as well as rate. The geographical distribution will depend on the location of the test sites and on meteorological conditions.

50. The main source of uncertainty in the computation of a population-weighted average from the tropospheric fall-out is that not even the present geographical distribution is sufficiently well known. However, local high values of deposit, which must be considered in all cases where a threshold assumption may be valid, have no relevance in the estimate of genetic effects to the population as a whole.

External exposure

51. If the present level of tropospheric fall-out is assumed to have a geographical variation over the range of 50-200 mc/km^2, the annual population weighted gonad dose is of the order of some tenths mrem[D78]. It must be emphasized that this estimate is much more uncertain than the estimates of the dose distributions from stratospheric fall-out.

Internal exposure

52. Assuming an air concentration of fission products at ground level of 10^{-15} c/l, the annual gonad dose from inhaled radioactive material has been estimated as 0.1 - 0.2 mrem. Few data are available to permit an estimate of the gonad exposure from short-lived fission products taken up with food. As a gamma exposure comparable with that from Cs^{137} in the body tissues would be

detectable in whole-body gamma spectrography, the lack of evidence for such concentrations of short-lived gamma emitters might be taken to indicate that the total internal exposure gives less than 1 mrem/year.

Total gonad dose from tropospheric fall-out

53. Because of the scant information, the estimate of the total annual gonad dose from tropospheric fall-out is very uncertain. It will be assumed here that this contribution is 0.5 mrem as an average for the world's population. As tropospheric fall-out will disappear when the injection is ceased, the resulting dose-rate is maintained only during the injection period.

54. An annual dose of 0.5 mrem during the period of injection implies a dose commitment of 0.5 mrem per year of injection to the troposphere at the present rate.

Summary tables

55. Tables III and IV show the combined contributions to the gonad exposure from stratospheric and tropospheric fall-out. The result is given as a dose commitment per year of injection, as defined in paragraphs 8 - 9.

Table III

Dose commitment at certain injection practices

	Dose commitment (mrem)		Total (mrem)
	Stratospheric fall-out	Tropospheric fall-out	
Per year of future injection according to assumption (a)	2.1	0.5	2.6
Per year of injection according to assumption (b)	4.8	0.5	5.3
As a result of test until the end of 1958	24	2.5	27

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Table IV

Maximum 30-year gonad dose

		30-year dose due to: Stratcsperic fall-out (mrem)	Tropospheric fall-out (mrem)	Total (mrem)	% of equilibrium
Assumption (a):					
Tests ceased at end of	1958	15	2.5	18	23
	1968	27	7.5	35	45
	1978	36	12.5	49	63
	1988	42	15	57	73
Tests continue		63	15	78	100
Assumption (b):					
Tests ceased at end of	1958	15	2.5	18	11
	1968	42	7.5	50	32
	1978	66	12.5	79	50
	1988	82	15	97	61
Tests continue		143	15	158	100

Contribution from carbon-14

56. When the total dose to which the human population has been committed over all time by weapons tests up to date is examined, it is necessary to consider also the contribution by an increase of carbon-14. It has been reported by Rafter and Fergusson,[10] working in the latitude of New Zealand, as well as by others in north temperate latitudes,[11] that the C^{14} content of atmospheric carbon has been increased by a fraction between 5 and 10 per cent since 1954, presumably because of nuclear test explosions. There is reason, since values from widely differing latitudes agree, to suppose that this increase applies to the lower atmosphere as a whole. There are also indications[10] that equilibration of this excess C^{14} with the carbon of surface ocean water is quite rapid.

57. It is reasonable to suppose that the excess C^{14} will, in a time short compared with the half-life of $C,^{14}$ come into equilibrium with the total biospheric pool of carbon, which exceeds the atmospheric carbon by a factor of about 60,[12] if oceanic inorganic carbon is included, and the possibility of long term exchange with other inorganic carbon is disregarded. It will be assumed that the present partition between stratosphere and troposphere of C^{14} formed in tests of nuclear weapons is similar to that of Sr^{90} and Cs^{137} where the stratospheric content $\overline{Q}_o = \overline{F}_r(0)/k =$ 15 mc/km^2 as an average over the surface of the earth, and $F_d(0) = 5$ mc/km^2. This leads to the assumption that only 1/4 of the total amount of C^{14} formed in the tests up to date is at present detectable at ground level.

58. From these assumptions, it follows that from the weapon tests up to date an increase of 1/3 to 2/3 per cent in the total biospheric C^{14} is to be expected. The present C^{14} has been estimated (cf. Annex B) to contribute a gonad dose rate of about 1.5 mrem/year. Hence the increase will be very small - about 5 - 10 µrem/year - but, because of the 5,600-year half-life of C^{14}, the total dose commitment will be the equivalent of this additional rate continued for 8,000 years. This will amount to some 40 - 80 mrem.

59. Most of this dose will be delivered so far in the future, that it is difficult to weight it properly for a comparison with the same dose delivered within a much shorter period. For this reason, the dose commitment due to C^{14} is considered here separately, and is not added directly to those which are delivered within relatively short periods, comparable with the human life-time, although it may well come to exceed them.

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60. Aside from the direct effect of beta radiation there is possibly an effect due to transmutation of C^{14} contained in the deoxyribonucleic acid of hereditary material, but the magnitude of such an effect has not been experimentally determined.

IV. BONE MARROW EXPOSURE

Dose effect relationship

61. The exposure of the bone marrow will be evaluated in the light of the possible induction of leukemia. Two assumptions will be treated in parallel because they give extreme results rather than because they are more likely than other assumptions. For both it will be postulated that the effect does not depend upon rate of exposure or fractionation of the dose. Any recovery has thus been disregarded. The assumptions are:

(A) There exists a threshold of the relevant dose, and

(B) There is no threshold, and the dose-effect relation is linear.

Threshold case

62. Where the existence of a threshold is assumed, it is appropriate to examine whether the highest exposure gives rise to a dose exceeding the threshold value. If this is not the case, the margin of safety can be estimated, i.e. it is possible to say by how much the mean exposure level can be increased before the threshold is exceeded. For this purpose, even if the average dose in a population is calculated, the spread around this average also needs to be assessed in some way.

63. The relevant dose (in the case of the threshold assumption) will be taken to be the 70-year mean marrow dose, averaged over the whole of the active marrow. This dose may not be relevant when only part of the marrow is exposed, but as the long-term marrow exposure due to fission products incorporated over a long period in the bone is fairly uniform, the 70-year mean marrow dose will be used here for the purpose of computation.

64. The true relevant dose may be the maximum dose to active marrow cells, wherever it occurs. However, no exposures can occur in bone marrow longer than over the life-time, and the 70-year dose is therefore adopted here in the absence of proof that a shorter period is appropriate.

65. If the total energy of the Sr^{90} body burden equivalent to 1 $\mu\mu c$ Sr^{90}/g of calcium is assumed to be dissipated in 7,000 g of bone, the average dose rate would be 2.64 mrem/year. It will be assumed here that some of the energy is delivered to the 1,500 g of red bone marrow but the energy delivered to the

yellow marrow or to tissues outside the skeleton will be disregarded. The mean values of the dose rates to bone marrow and spongious bone have been taken to be 0.6 and 0.9 mrem/year respectively.[13,14] Assuming that spongious bone constitutes 10 - 12.5 per cent of the total bone mass this implies dose rates of 2.7 and 2.5 mrem/year to compact bone and total bone respectively (cf. Table V).

Table V

Mean and maximum dose rates in mrem/year for chronic poisoning with 1 $\mu\mu$c Sr^{90} per gram of calcium[13]

	A. Uniform labelling		B. Uneven distribution factor = 2	
Bone marrow	Maximum 3.0 (1.8)	Mean 0.6	Maximum 5.9 (3.6)	Mean 0.6
Spongious bone	1.7	0.9	3.4	0.9
Compact bone	2.7	2.7	5.4	2.7
Compact and spongious bone	2.7	2.5	5.4	2.5

Figures in brackets give the maximum bone marrow dose inside spongious bone.

66. In considering the maximum dose rates for cases A and B the geometrical distribution of the uniform labelling is the only factor which has been taken into account.[13] For bone marrow the maximum dose rate will be obtained within Haversian systems inside compact bone. The difference between the values 2.7 and 3.0 in table V represents a difference in stopping power. The maximum values due to uneven distribution are based only on differences in mineralization between regions with linear dimensions of the same order as the Y^{90} β-range. The influence of microscopic changes in the mineralization has not been allowed for, yet it is believed that this is relatively unimportant, most probably less than a factor of 2. The ratio of maximum to mean marrow dose will be about 10, which includes the factors 2, for uneven distribution of the Sr^{90}, and 5, for the increased dose-rate in enclosed cavities.

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67. Knowledge of the threshold level would imply evidence in support of the threshold theory. No such information exists, and all that can be said from the available data is that a possible threshold may lie anywhere between 0 and 400 rem.[15]

Case of non-threshold, linear dose-effect relation

68. On the alternative extreme assumption that no threshold exists and that the dose-effect relation is linear, the number of persons who will develop leukemia after a certain marrow exposure can be estimated as the product of the population involved (which will be assumed to be constant), the appropriate dose and a dose-effect constant. The appropriate dose is the per capita mean marrow dose, where "mean marrow dose" denotes the average dose over the whole mass of active marrow. An increment δD of the per capita mean marrow dose will be assumed to result in a number δN of leukemia cases in the future, computed as:

$$\delta N = K_1 \cdot P \cdot \delta D \qquad (39)$$

where P is the population and K_1 the dose-effect constant for induction of leukemia.

69. An estimate of the dose-effect constant for induction of leukemia can be made from the present data on number of occurrences following a certain exposure (see Annex G). It will be assumed that a single exposure of 1 rem to the entire red marrow will result in 1.5 annual cases per million exposed for a period of 15 years following the exposure.* The total number of cases is therefore

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* If the risk of developing leukemia is not limited to the first 15 years following the exposure, but maintained at constant value throughout life, the increment dN_k will be different for each age-group k of the population exposed to a dose dD. The corresponding dose-effect factor would be $1.5\ (70 - \tau_k)$ rem^{-1} per million where τ_k denotes the age at the time of exposure. However, the available data seem to indicate a decrease of the annual rate of incidence after 10 years[16,17] and this possibility will not be considered here. As the mean age in a model population is 35 years, the average dose-effect factor would be $35 \cdot 1.5 = 52$ rem^{-1} per million, which differs from the assumed factor only by a factor of 2.3.

23 per million exposed, and

$$K_1 = 23 \text{ rem}^{-1} \text{ per million}$$

This factor can be applied to all individuals having a life expectancy of more than 15 years at the time of exposure. In a model population where the age of death is 70 years, it is hence valid for 80 per cent of the population. In the following it will be taken to apply to the population as a whole.

Marrow exposure from stratospheric fall-out

70. In the case of stratospheric fall-out, the most important source of marrow exposure is strontium-90 incorporated in the bone. There is also a marrow exposure from caesium-137, both external and internal. The marrow exposure from Cs^{137} varies with time in the same way as the gonad exposure from this source, and is approximately of the same magnitude. It is therefore described by the curves in figure 3. As it amounts to only about 5 per cent of the marrow exposure from Sr^{90}, it will be disregarded in the following estimate, and the marrow dose from Sr^{90} will be taken as the only significant contribution from stratospheric fall-out.

71. The Sr^{90} marrow exposure differs from the Cs^{137} gonad exposure not only in magnitude but also in the distribution over time. The gonad exposure is a function of the fall-out rate and deposit at the time of exposure, since Cs^{137} is fairly rapidly excreted. Because of the long retention of Sr^{90}, however, the marrow will be exposed over a long period of time following the uptake, and the relation between the fall-out functions and the marrow exposure at a certain time is relatively complicated.

Total bone burden of strontium-90

72. The relationship between the Sr^{90} body burden of the population and that of the dietary has previously been approximated (Annex D) by assuming that all of the calcium in the body will at any time have a strontium burden reflecting that of the dietary. This is obviously an overestimate, but is probably not in serious error for younger individuals because of the time pattern of Sr^{90} contamination. A more rigorous and general evaluation is possible from

mathematical consideration of rates of calcium and strontium accretion in relation to the projected time-patterns of Sr^{90}/Ca ratios. Such treatment provides two advantages: (a) more realistic value for the Sr^{90} burden is forthcoming and (b) general relationships in regard to age, date of birth, and pattern of Sr^{90}/Ca ratios with time that permit estimations of mean marrow doses.

73. Sr^{90} is taken up by the body through food-chains. The change in the ratio Sr^{90}/Ca during each step from soil to bone is often described by the help of discrimination factors, but for the purpose of these calculations the rate of Sr^{90} uptake will be assumed to follow the empirical expression (see Annex D):

$$c(t) = a_r \cdot F_r(t) + a_d \cdot F_d(t) \qquad (40)$$

where $c(t)$ = ratio Sr^{90}/Ca in the minerals entering bone

a_r and a_d = constants with different values for various food-chains.

74. Equation (40) makes it possible to determine the quantity (q) of Sr^{90} that is incorporated in the bone at the same time as a certain mass (α) of calcium:

$$q(t) = c(t) \cdot \alpha \qquad (41)$$

In the following q and α will denote the rate of incorporation of Sr^{90} and calcium respectively. The net rate of increase will depend on the rate of turnover of earlier incorporated material.

75. By using an empirical formula of the type (40) that may be extrapolated over a hundred years, the bone burden of Sr^{90} can be computed by help of $c(t)$ and a number of assumptions on the calcium and strontium metabolism. It will be shown that the final result, in form of the infinite-time integral of the dose-rate, or the maximum 70-year dose, does not depend critically on the assumptions about the metabolism of bone (see paragraph 101).

76. The rate at which dietary Ca and Sr^{90} enter the skeleton depends on several processes the most important of which are formation of new bone mineral and resorption of existing bone mineral. For the system under consideration the processes of surface exchange of ions between bone and blood can be neglected. The uptake of calcium can then be approximated by equations based on the difference between rates of accretion and resorption.

77. Evidence is available as to the way in which the human body content of calcium increases with age.[17] This evidence may be adequately approximated for the purposes of these calculations by assuming that the body calcium increases linearly with age from 6 months after conception up to age of 20 years. The errors introduced by replacing the sigmoid growth curve by a straight line with a discontinuity at age 20, are of the less importance since the main concern is with the dose integral to the age of 70.

78. Bone salt metabolism has been studied in detail and models of varying complexity have been proposed.[18-21] The simple model described below is in keeping with the principles reflected in the reference material. With the approximation of the body calcium increase, the net uptake of calcium is governed by the equations:

(τ < 20 years)

$$\frac{dB(\tau)}{d\tau} = \alpha - k_o(\tau) \cdot B(\tau) = \text{const.} = \beta \qquad (42)$$

where $B(\tau) = \beta\tau$, and $\alpha = \beta + k_o(\tau) \cdot B(\tau) = \beta(1 + k_o\tau)$ (42a)

(τ > 20 years)

$$\frac{dB(\tau)}{d\tau} = \alpha - k_o(\tau) \cdot B(\tau) = 0 \qquad (43)$$

where $B(\tau) = \text{const.} = B_a$, and $\alpha = k_o(\tau) \cdot B_a$ (43a)

The symbols are:

α = rate of total calcium accretion,

$k_o(\tau)$ = fraction of calcium turned over per unit time,

β = constant net increase of calcium per unit time under age 20,

$B(\tau)$ = mass of bone calcium at age τ,

B_a = mass of bone calcium in an adult.

79. No satisfactory evidence is available as to how the fractional calcium turnover rates vary with age in man. The changes in turnover rates could possibly be represented by power functions, exponential functions or series of exponential functions. However, there are no data that permit mathematical treatment. It is necessary then to determine how different values of the turnover rate will affect the results obtained.

80. In the general expression

$$\frac{dB}{d} = \alpha - k_o(\tau) \cdot B(\tau) \qquad (44)$$

it is useful to consider two extreme values for k_o

(I) If $k_o = \infty$, an infinite amount of calcium is taken up (and turned over) per unit time. This implies that the bone is continuously in complete equilibrium with its environment, and the apparent concentration of Sr^{90} in bone, $s(t, \tau)$, is at any time

$$s(t, \tau) = c(t) \qquad (45)$$

(II) If $k_o = 0$, calcium is acquired only during the period of growth, at the rate β, and then retained during the life-time.

81. As any retention curve can be approximated by a series of exponential functions which represent various fractional turnover constants, the result obtained with these expressions may be expected to fall somewhere between the limits set by the extreme cases (I) and (II). As these extremes will be shown to give quite similar results, more accurate assumptions do not seem to be called for.

82. When assumptions for the calcium metabolism have been made, the bone burden of Sr^{90} can be calculated from the equation

$$\frac{dQ(\tau)}{d\tau} = q - k_1 \cdot Q(\tau) \qquad (46)$$

where q = uptake of Sr^{90} per unit time = $c(t) \cdot \alpha$,

k_1 = fraction of Sr^{90} turned over per unit time, $k_1 = k_{Sr} + \lambda$, where k_{Sr} is the biological turnover factor and λ is the radioactive decay constant,

$Q(\tau)$ = total amount of Sr^{90} in bone.

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83. There is reasonably good evidence that the turnover rates of calcium and strontium are essentially equal. The influence of various assumptions on the strontium retention will be discussed in paragraph 100. The use of a constant k_1 in equation (46) implies that the retention of strontium in bone is an exponential function of time. The following calculations will be performed on the basis of this assumption, and the possible error introduced hereby will be estimated.

84. The apparent concentration of Sr^{90} in bone, i.e. the ratio $s(t,\tau) = Q(t,\tau)/B(\tau)$, can now be computed by integration of equation (46), assuming that also k_o is constant.

(τ < 20 years)

$$s(t,\tau) = e^{-k_1\tau} \cdot \frac{1}{\tau} \cdot \int_0^{\tau} c(t) \cdot (1 + k_o\tau) \cdot e^{k_1\tau} \, d\tau \qquad (47)$$

(τ > 20 years)

$$s(t,\tau) = e^{-k_1\tau}\left[\frac{1}{20} \cdot \int_0^{20} c(t) \cdot (1 + k_o\tau) \cdot e^{k_1\tau} \, d\tau + k_o \cdot \int_{20}^{\tau} c(t) \cdot e^{k_1\tau} \, d\tau\right] \qquad (48)$$

Empirical formulas for c(t)

85. To use equations (47) and (48) it is necessary to know c(t). As mentioned in paragraph 73, empirical formulas may be derived from available data, of the type (40). In practice it will be assumed that the fall-out rate dependent term can be disregarded in long term extrapolations. Hence the following equation will be used:

$$c(t) = a \cdot F_d(t) \qquad (49)$$

86. In Annex D (paragraphs 118-120), data and constants have been developed that relate the accumulated fall-out deposit of Sr^{90} to the Sr^{90}/Ca ratio found in milk (Perry, N.Y. and the United Kingdom) and rice (Japan). These values will be used in the following to calculate typical radiation doses, assuming that these two foods constitute the entire source of dietary calcium and Sr^{90}. The constant a can be derived from the Sr^{90}/Ca ratio in the two diets and the

discrimination factor milk-bone to give the Sr^{90}/Ca ratio in the new material incorporated in bone.*

(1) For a milk diet:

$$a_M = 0.15 \ \mu\mu c \ Sr^{90}/g \ Ca \text{ per } mc/km^2$$

(2) For a rice diet:

$$a_R = 0.9 \ \mu\mu c \ Sr^{90}/g \ Ca \text{ per } mc/km^2$$

Marrow dose rate

87. The mean marrow dose rate will be proportional to the apparent concentration of Sr^{90}, $s(t,\tau)$:

$$\frac{dD(t,\tau)}{dt} = \gamma \cdot s(t,\tau) \qquad (50)$$

The proportionality factor γ will be taken to be 0.6 mrem/year per strontium unit, whereas the dose-rate in the bone will be taken to be 2.5 mrem/year per strontium unit (cf. paragraph 65).

88. The uncertainty involved in the estimate of the best value of the dose constant γ is due mainly to lack of information on the location of the bone strontium with respect to the active marrow, the difficulty of calculating the actual dose distribution from the information of the strontium distribution, and to uncertainty with regard to the size distribution of the marrow cavities.

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* This constant gives the Sr^{90} ratio in the newly formed bone. In the case of rapid excretion during a short period after the uptake (power function retention), it is assumed that Sr^{90} and Ca are excreted at the same rate. If this is the case, the ratio of the fractions that are retained for longer periods will remain the same, and equations (41), (42 a) and (43 a) will still give the amount of Sr^{90} that is taken up to be incorporated in bone over long periods of time. If this is not the case, $c(t)$ should denote the Sr^{90}/Ca ratio of the more firmly incorporated material. In the latter case, the constant a will have lower values if Sr^{90} is excreted more rapidly than calcium.

89. As the dose rate is a function of date of birth as well as of calendar date, it cannot be represented by a single curve for each assumption on injection practice. In the following sections, the infinite time integral of the per capita mean marrow dose-rate will be calculated so as to give the dose commitment for each practice: the maximum 70-year integrals will also be computed, so as to indicate the margin of safety in the case of the threshold assumption.

Infinite time integral

90. The dose commitment for a certain injection practice can be calculated as the infinite time integral of the per capita mean marrow dose rate. In the following the dose commitment has been assessed by help of a different approach, considering the effect of an infinitesimal uptake of Sr^{90} at a certain time.

91. The Sr^{90} taken up into bone during an infinitesimal period dt, at time t can be expressed by

$$dQ = \alpha \cdot c(t)dt \qquad (51)$$

An individual of age u at the time of uptake will at a later age τ have retained

$$dQ(u, \tau) = dQ(u, u) \cdot e^{-k_1(\tau - u)} \qquad (52)$$

92. By integrating the dose rate caused by this retained Sr^{90} over the balance of life, one obtains the life time dose increment to the marrow due to the individual uptake during the period dt at age u and time t:

$$dD(u, t) = F_m(u)\ \gamma \cdot c(t)dt \qquad (53)$$

The dose increment factor $F_m(u)$ for individuals with an expected life span of m years will be shown to be (see paragraph 97)

Under age 20 years $$F_m(u) = \frac{\alpha}{k_1 B_a} \cdot (1 - e^{-k_1(m - u)}) \qquad (54)$$

Over age 20 years $$F_m(u) = \frac{k_o}{k_1} \cdot (1 - e^{-k_1(m - u)}) \qquad (55)$$

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In the general case $\frac{\alpha}{B_a} = k_o \cdot \frac{B(u)}{B_a} + \frac{\beta}{B_a}$ and with the simplified linear model of bone growth $\frac{\alpha}{B_a} = \frac{1}{20}(1 + k_o u)$, for $u < 20$ years.

93. The value $d\bar{D}$ of the life time dose increment averaged over the whole population subject to the uptake during the period dt at time t can be calculated as

$$d\bar{D}(t) = \frac{1}{m}\int^{m} dD\, du = \gamma \cdot c(t)\, dt \cdot \bar{F}_m \qquad (56)$$

where

$$\bar{F}_m = \frac{1}{m} \cdot \int_0^m F_m(u)\, du \qquad (57)$$

94. With the average dose increment factor $\bar{F}_m$ known for a population where the mean life is m years, the dose commitment for an injection practice causing the contamination c(t) can be calculated as

$$D_\infty = \bar{F}_m \cdot \gamma \cdot \int_{-\infty}^{+\infty} c(t)\, dt \qquad (58)$$

95. The dose increment factor $F_m(u)$ is given in figure 5, assuming the accretion of skeletal calcium reported by Mitchell et al.[17] The biological interpretation of the factor is discussed in the text to the figure. The average values $\bar{F}_{70}$ for a model population where every member lives to age 70 years are indicated in the diagrams. It will be shown that $\bar{F}_m$ is not critically dependent on either the rate of calcium and strontium turnover or the mean age of the population. The simple linear model for calcium accretion under age 20 years would give results indicated by the broken lines on figure 5.

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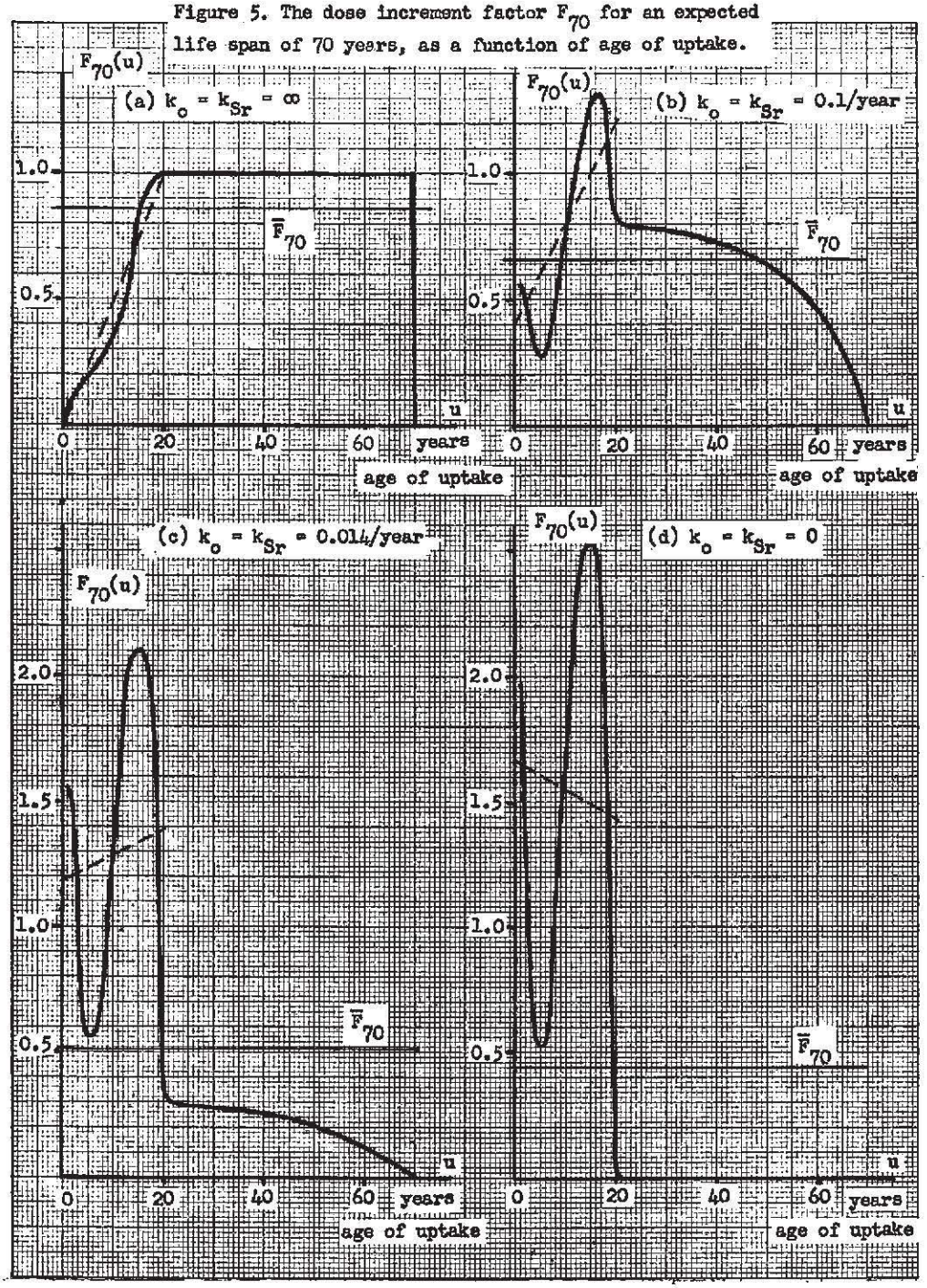
Figure 5. The dose increment factor F_{70} for an expected life span of 70 years, as a function of age of uptake.



a) Extreme case of instantaneous equilibrium between bone and environmental Sr^{90}, with infinite turnover constant. Note the high dose this would give to the adult.

b) Biological half life for Sr assumed to be 7 years ($k_{Sr} = 0.1$/year).

c) Biological half life for Sr assumed to be 50 years ($k_{Sr} = 0.014$/year). Note the increasing importance of uptake and retention in childhood, and the reduced uptake in the adult.

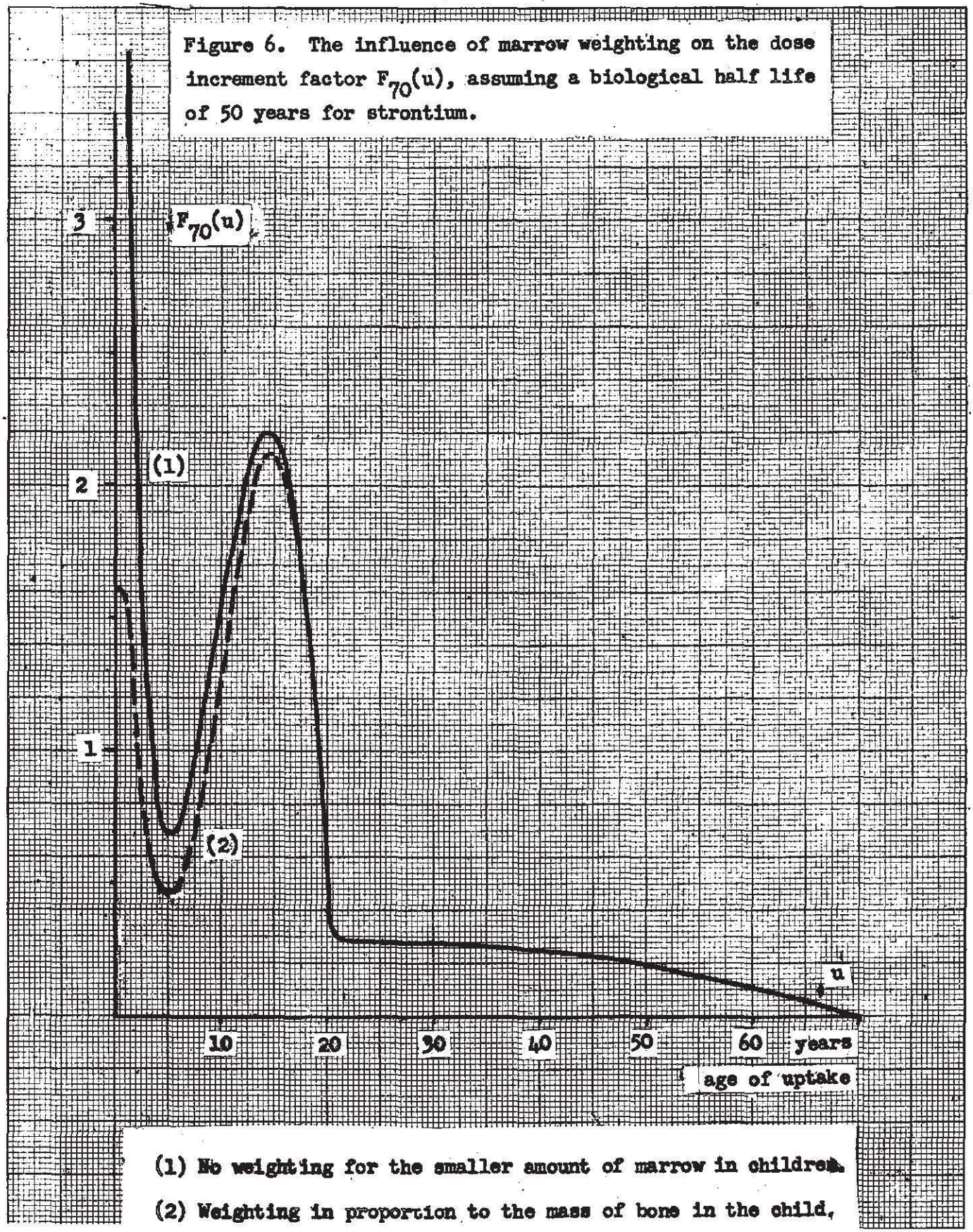
96. The formulas (54) and (55) have been derived on a specific assumption about the significance of the exposure of marrow in children. On the non-threshold, linear dose-effect assumption, the mean marrow doses must be weighted for mass of marrow. The following two extreme cases have been considered, namely

(1) No weighting for the smaller amount of marrow in children, and

(2) Weighting of the child dose in proportion to the mass of bone.

As there is more marrow in proportion to bone in a child than in an adult, the case (2) will give an over-correction, and the true result can be expected to lie between the two cases (1) and (2). The influence of marrow weighting is illustrated by figure 6.

Figure 6. The influence of marrow weighting on the dose increment factor $F_{70}(u)$, assuming a biological half life of 50 years for strontium.



(1) No weighting for the smaller amount of marrow in children.

(2) Weighting in proportion to the mass of bone in the child.

97. In the case that the marrow is weighted in proportion to the mass of bone, the formulas (54) and (55) can be derived from (53) where dD(u, t) is the integral of the dose-rate caused by $dQ(u,\tau)$ over the balance of life:

$$dD(u, t) = \int_{u}^{m} \frac{d}{d\tau}(dD)\, d\tau \qquad (59)$$

and

$$\frac{d}{d\tau}(dD) = \frac{\gamma}{B_a} \cdot dQ(u,\tau) \qquad (60)$$

The integration gives

$$u < 20 \text{ years} : dD(u,t) = \gamma \cdot c(t)\, dt \cdot \frac{\alpha}{k_1 \cdot B_a}\left(1 - e^{-k_1(m-u)}\right) \qquad (61)$$

$$u > 20 \text{ years} : dD(u,t) = \gamma \cdot c(t)\, dt \cdot \frac{k_o}{k_1}\left(1 - e^{-k_1(m-u)}\right) \qquad (62)$$

98. In the case that no marrow weighting is made, the formula (60) must be replaced by the following expression for $u < 20$ years

$$\frac{d}{d\tau}(dD) = \frac{\gamma}{B(\tau)} \cdot dQ(u,\tau) \qquad (63)$$

which with the simple linear model of bone growth leads to

$$u < 20 \text{ years} \qquad dD(u,t) = \gamma \cdot c(t)dt \cdot (1 + k_o u)\left\{e^{k_1 u}\left[E_i(k_1 u) - E_i(20k_1)\right] + \right.$$
$$\left. + \frac{1}{20k_1}\left(e^{-k_1(20-u)} - e^{-k_1(m-u)}\right)\right\} \qquad (64)$$

where E_i denotes the exponential integral.

/...

Accordingly the dose increment factor will be

$$F_m(u) = (1 + k_o u) \cdot \left\{ e^{k_1 u} \left[E_i(k_1 u) - E_i(20k_1) \right] + \right.$$
$$\left. + \frac{1}{20\, k_1} \left(e^{-k_1(20 - u)} - e^{-k_1(m - u)} \right) \right\} \qquad (65)$$

The influence of the marrow weighting is shown in figure 6. All other diagrams have been derived from the formulas (54) and (55) and not from (65), i.e. they illustrate the marrow-weighted case.

99. Figure 7 shows the dose increment factor $F_m(u)$ for the special case that $k_o = k_{Sr} = 0.014$ and various values of the expected life (m).

100. Figure 8 shows how $F_m(u)$ will be affected in the case the turnover of strontium is more rapid than that of calcium.

101. Figure 9 summarizes the results by showing how the average dose increment factor $\overline{F}_m$ varies with the turnover rate of calcium and the expected life in a population. The variation is apparently very limited, ranging from 0.5 to 0.8 for likely values of k and m.

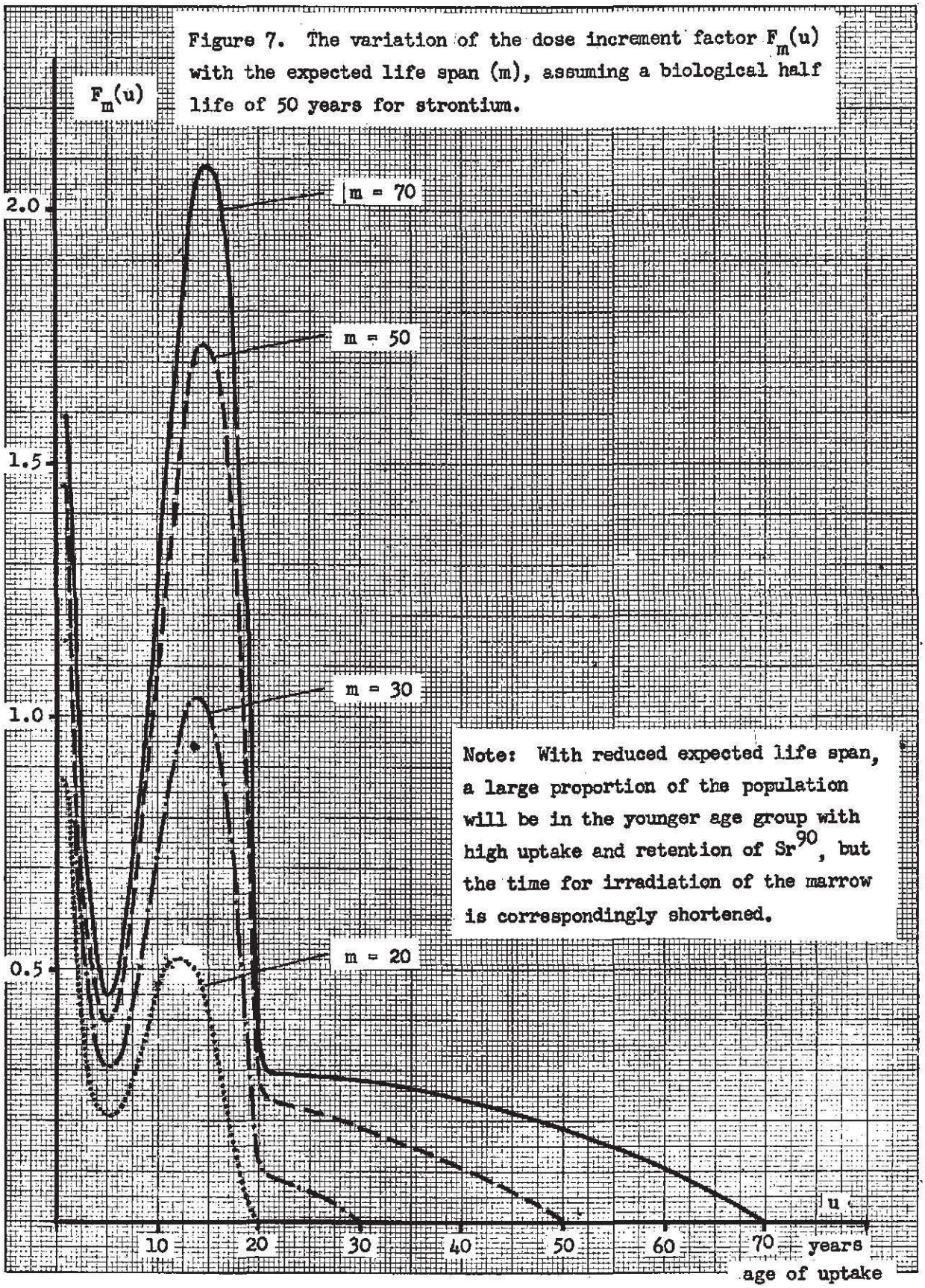
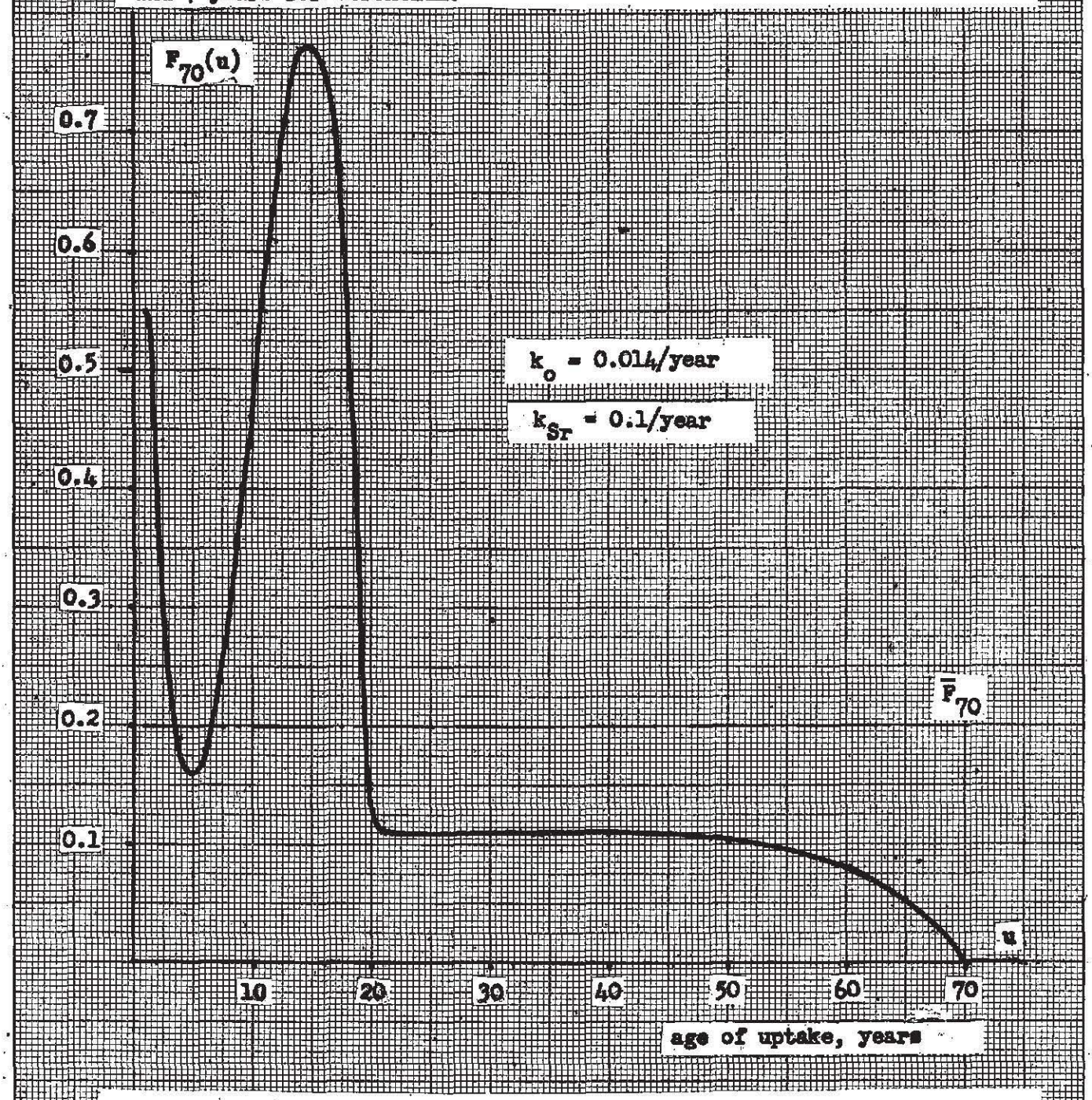


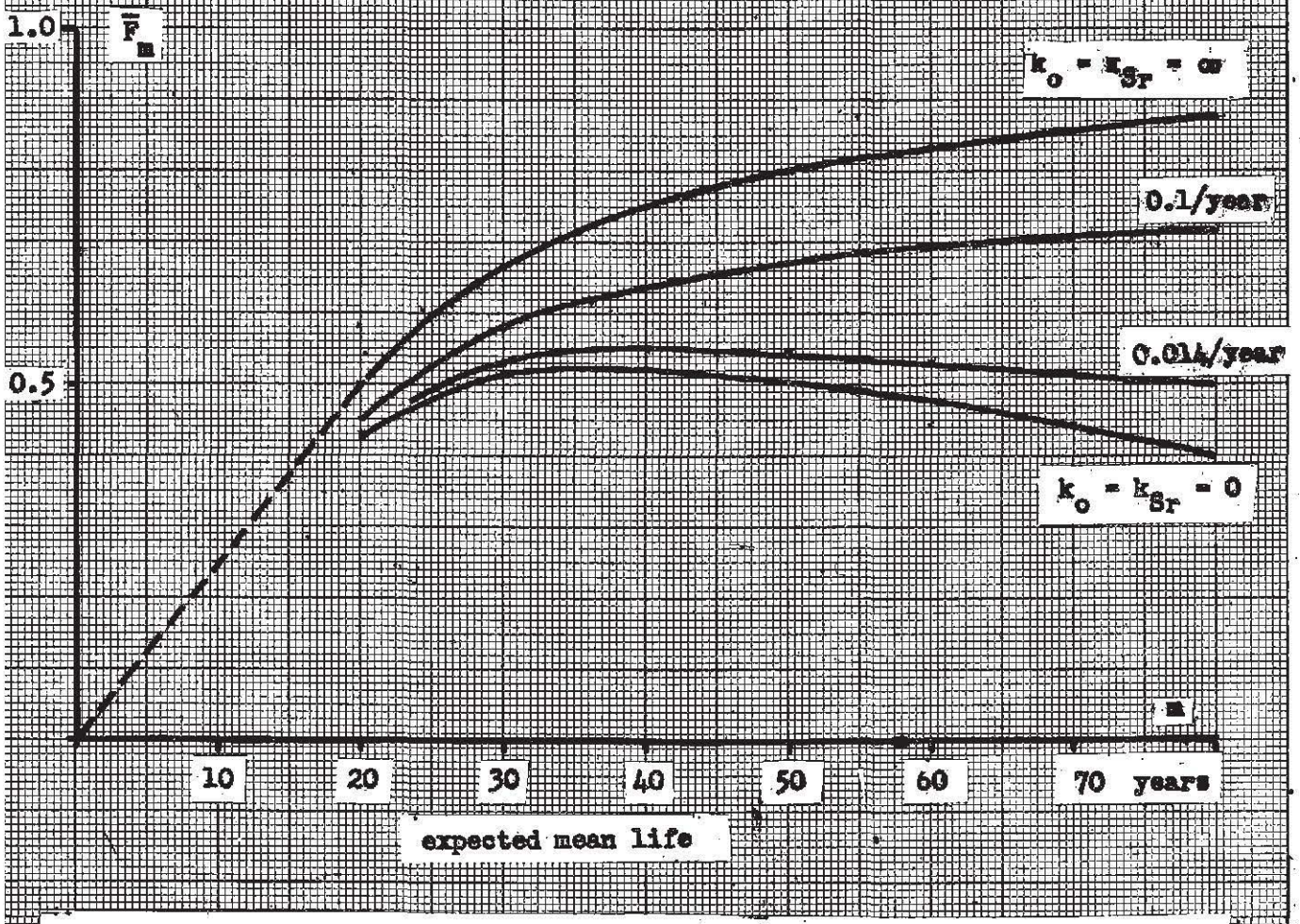
Figure 7. The variation of the dose increment factor $F_m(u)$ with the expected life span (m), assuming a biological half life of 50 years for strontium.

Figure 8. The dose increment factor $F_{70}(u)$ as a function of age of uptake of Sr^{90}, assuming a biological half life of 50 years for calcium and 7 years for strontium.



Note: This represents an extreme case based on the assumption that strontium is turned over in the skeleton at a much faster rate than calcium. Animal experiments and data from the radium poisoning cases in man suggest that both turnover rates are extremely slow in the adult.

Figure 9. The population average of the dose increment factor for various turn over constants as a function of the expected mean life.



Note: For life spans between 30 and 50 years and for values of $k_{Sr} = k_o$ in bone ranging from 0 to ∞, the range of the mean population dose increment factor $\bar{F}_m$ is only 0.5 - 0.8. The reason for this remarkably narrow range is the compensating effects of changes implied in the various assumptions which have been made. For example, a more rapid turnover will reduce the retention of strontium taken up by a child, but will increase the uptake and exposure of the adult. With a shorter mean life span for the population, a larger proportion will be in the younger age group with a high uptake of strontium, but the total life-time exposure is reduced.

102. As the $\overline{F}_m$ is not critically dependent on the assumptions on bone metabolism, the retention of calcium will be approximated, for the purpose of these calculations, by a single exponential function of time, with $k_o = 0.014$, which corresponds to a half-life of 50 years. This is the value that has been suggeste by the ICRP. If Sr^{90} is assumed to have the same biological half-life as calcium the value of k_1 will be 0.04. For the following calculations $\overline{F}_m$ will be taken t be 0.5. If no correction for marrow mass is made, the factor will be 0.65 for m = 70 years in the case illustrated in figure 6.

103. With $\overline{F}_m = 0.5$ and $\gamma = 0.6$ equations (58) and (49) give

(1) For a milk diet $$D_\infty = 0.045 \int_{-\infty}^{+\infty} F_d(t)\, dt \qquad \text{(mrem per mc/km}^2\text{)} \quad (66)$$

(2) For a rice diet $$D_\infty = 0.27 \int_{-\infty}^{+\infty} F_d(t)\, dt \qquad \text{(mrem per mc/km}^2\text{)} \quad (67)$$

104. The dose commitment per year of injection must be the same whatever time t the injection occurs. It can therefore be calculated from equilibrium considerations, using equations (21) and (23) as

$$D_\infty^1 = \overline{F}_m \cdot \gamma \cdot a \cdot F_d(\infty) \qquad (68)$$

which yields 36a and 82a respectively on assumptions (a) and (b) of the injection rate. With the values for the constant a from paragraph 86, this gives the dose commitments listed in table VI.

Table VI

Dose commitment resulting from certain injection practices

	Dose commitment (mrem) per year of injection	
	Assumption (a)	Assumption (b)
(1) For a milk diet	5.4	12
(2) For a rice diet	32	73

Figure 10. 70-year per capita mean marrow dose (population-weighted wo
average) as a function of time of birth, if tests continue on assumptio
a).

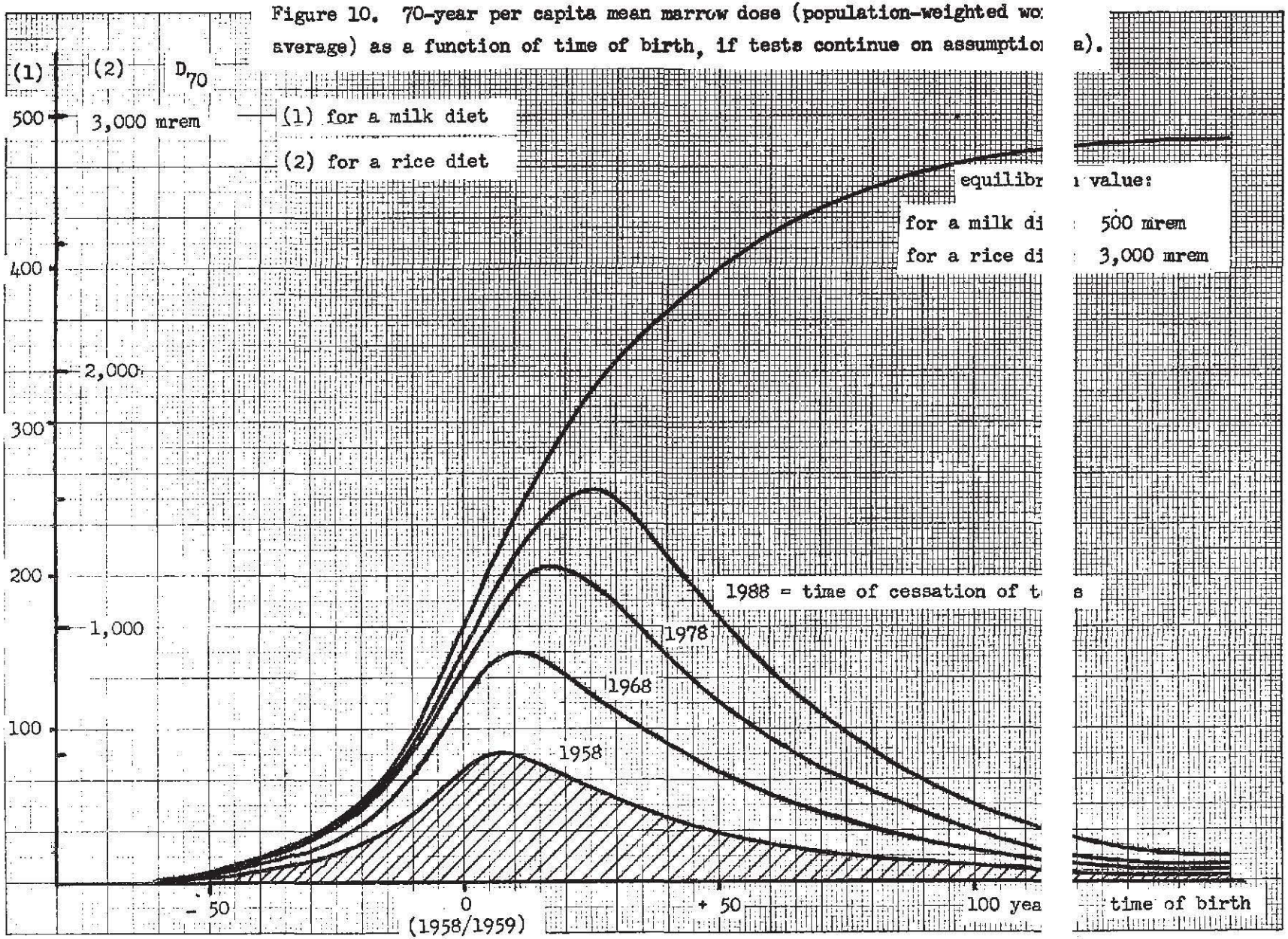
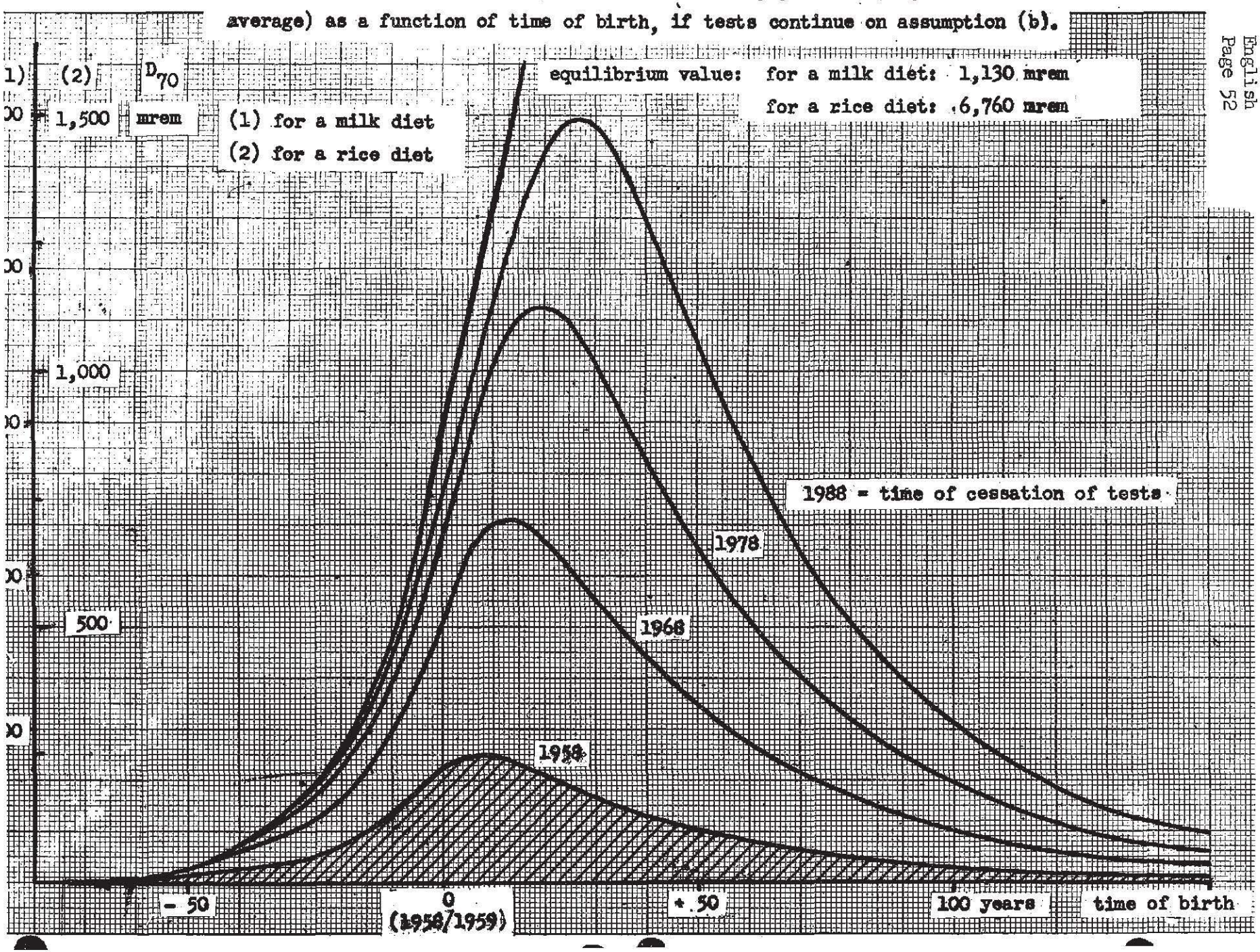


Figure 11. 70-year per capita mean marrow dose (population-weighted world average) as a function of time of birth, if tests continue on assumption (b).



70-year integrals of the mean marrow dose-rate

105. The life-time mean marrow dose as a function of time of birth t_b will be calculated as

$$D_{70}(t_b) = \int_0^{70} \frac{dD(t,\tau)}{d\tau}\, d\tau = \int_0^{70} \gamma \cdot s(t,\tau)\, d\tau \qquad (69)$$

using the expressions (47) and (48) for $s(t,\tau)$. This is a numerically complicated calculation, which has been performed for various values of injection rate and time of cessation of injection. The result is shown graphically in figures 10 - 11, and the maximum 70-year doses are given in table VII.

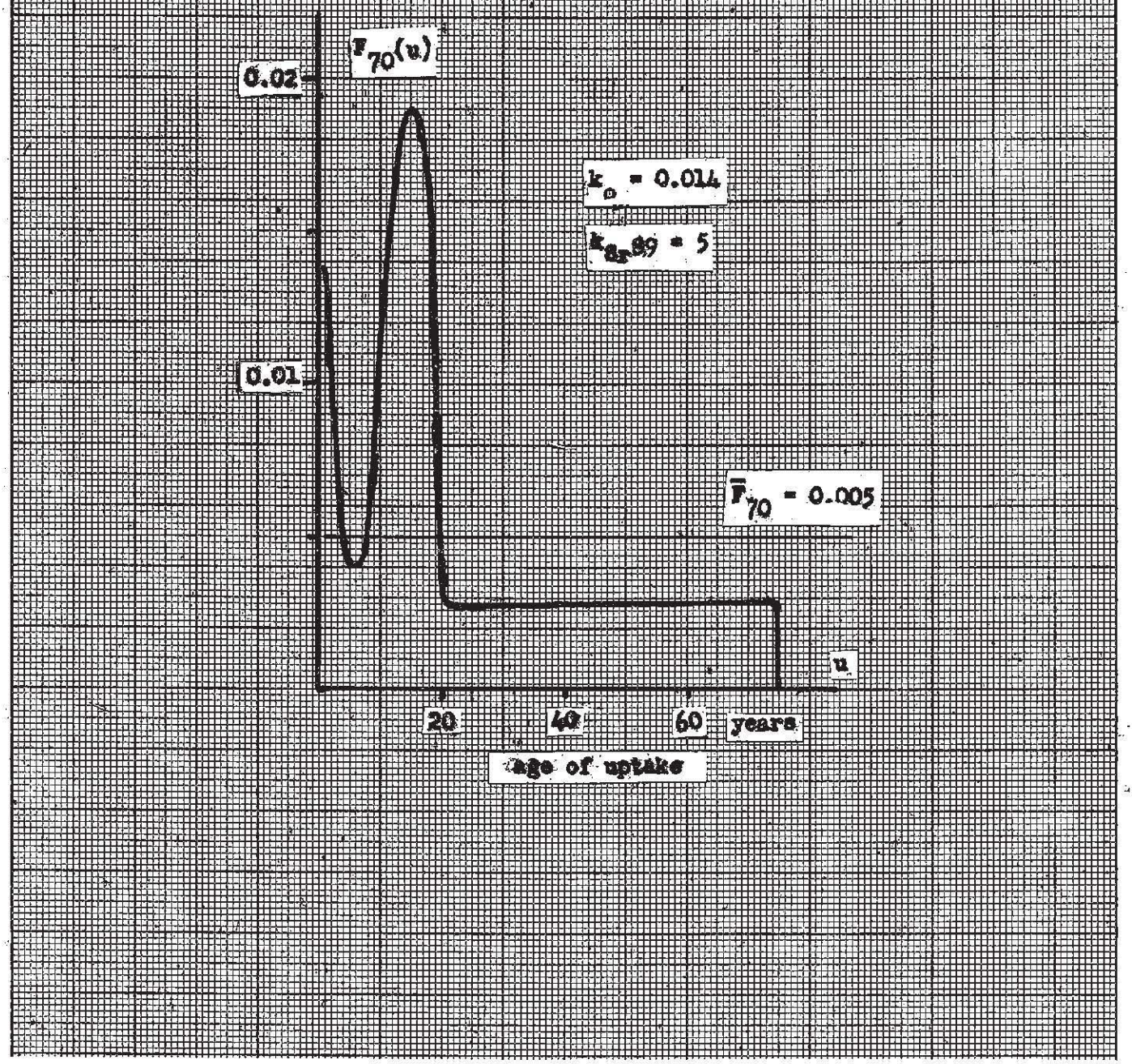
Contribution from tropospheric fall-out

106. Figure 12 gives an example of the variation of the dose increment factor $F_m(u)$ according to equations (54) and (55) for an uptake $\alpha \cdot c(t)dt$ of Sr^{89}, which is the most important isotope to consider in the estimate of marrow exposure from tropospheric fall-out. With $\bar{F}_m = 5 \cdot 10^{-3}$, the dose commitment for a practice resulting in the contamination $c(t)$ is found to be

$$D_\infty = 5 \cdot 10^{-3} \cdot \gamma \int_{-\infty}^{+\infty} c(t)dt \qquad (70)$$

/...

Figure 12. The dose increment factor $F_{70}(u)$ in the case of Sr^{89} with a physical half life of 51 days ($k_{Sr^{89}} = 5$/year).



107. In the case of Sr^{89} the dose constant γ is taken to be 1 mrem/year per $\mu\mu c$ Sr^{89}/g Ca. It will be assumed that c(t) is 0.5 times the concentration of Sr^{89} in milk, for which figure 13 shows some reported data. The integral of c(t) over one year can be estimated as about 20 $\mu\mu c/g$ Ca per year. Accordingly the dose commitment for one year of injection is

$$D_{\infty}^{1} = 5 \cdot 10^{-3} \cdot 1 \cdot 20 = 0.1 \text{ mrem}$$

108. The formula (47) may be used for an estimate of the apparent concentration of Sr^{89} in a child. A simplified model of the seasonal variation of Sr^{89} in milk has been assumed (on the basis of the Canadian data [22] in figure 13) for calculation of the contamination of the bone of infants born at a time so that the calcification starts at the beginning of the peak of environmental contamination. For these infants, the mean marrow dose during the first year will be about 10 mrem,* and the 70-year mean marrow dose some 20 mrem if the tropospheric injection is continued. For children born at other times of the year, however, the dose will be smaller, and the per capital mean marrow dose in the whole populations, including adults, will be of the order of 0.1 mrem per year.* The mean marrow dose rate for the infants is shown in Figure 14.

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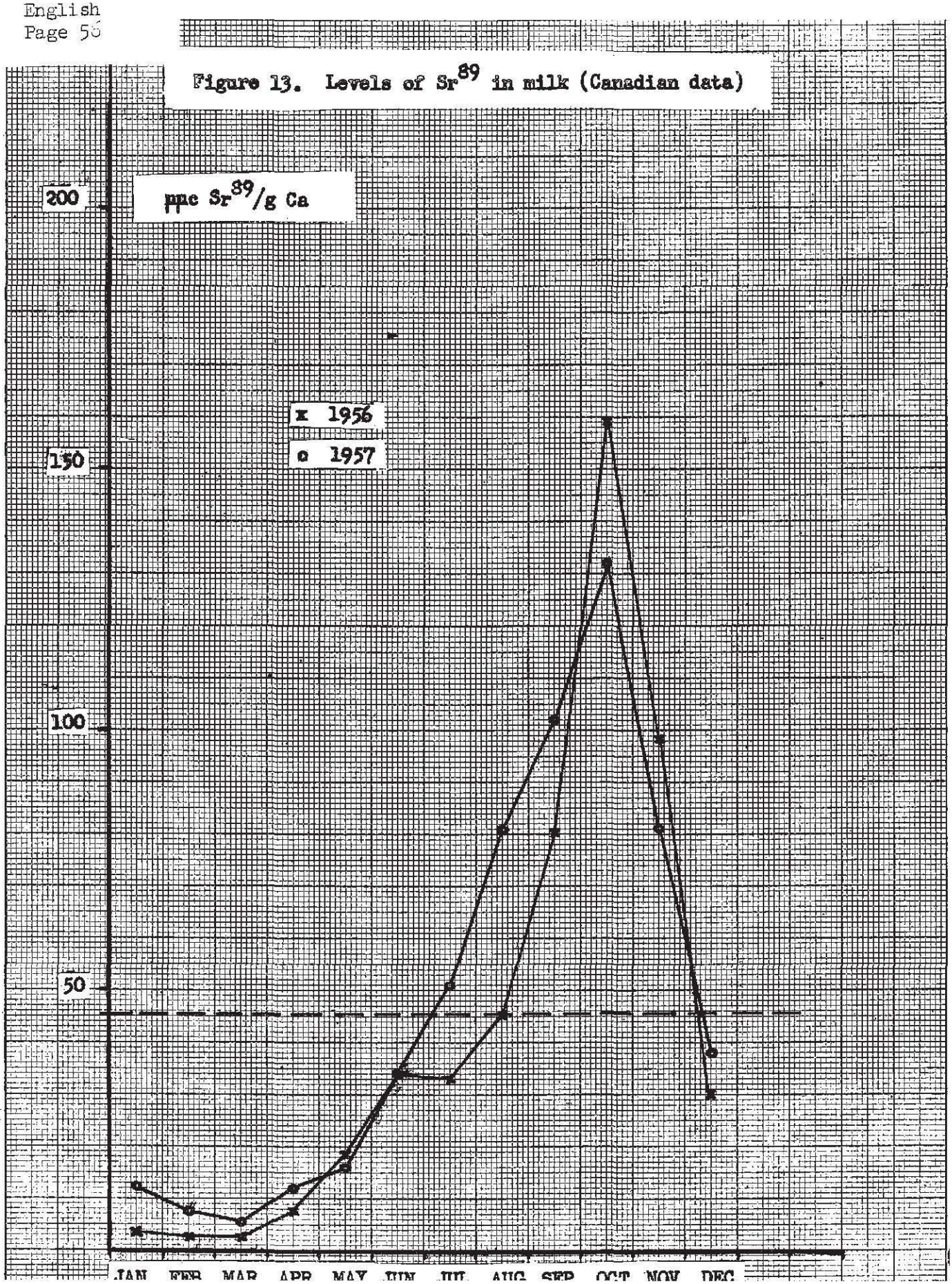
* In the case of the threshold assumption, where the maximum marrow dose may be relevant, it is important to note that the maximum marrow dose for acute poisoning with radiostrontium may exceed the mean marrow dose by a factor of 25-50 compared to the factor 10 for chronic poisoning.[11]

Figure 13. Levels of Sr^{89} in milk (Canadian data)



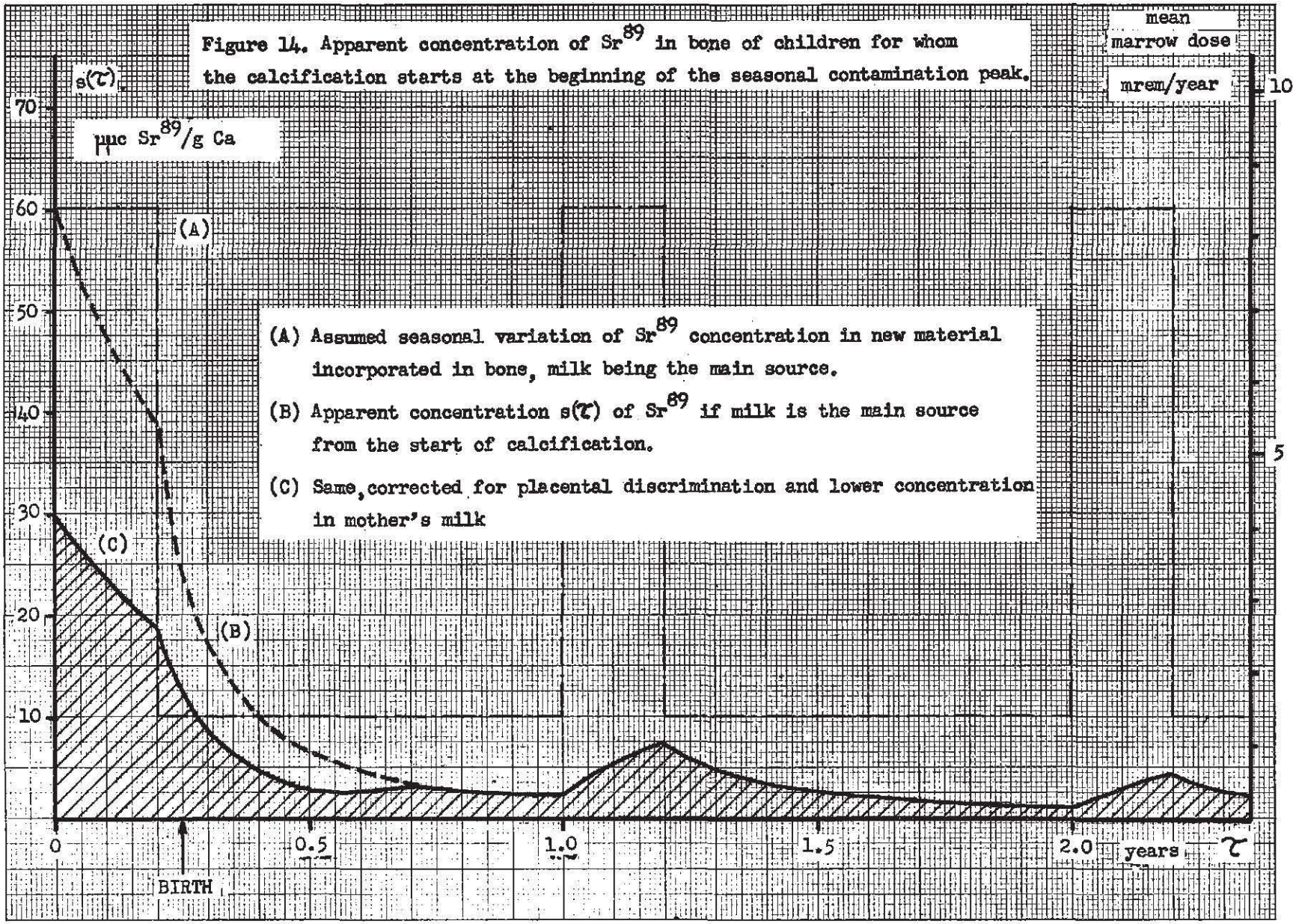


Figure 14. Apparent concentration of Sr^{89} in bone of children for whom the calcification starts at the beginning of the seasonal contamination peak.
s(τ)
μμc Sr^{89}/g Ca
70
60
50
40
30
20
10
0
(A)
(B)
(C)
(A) Assumed seasonal variation of Sr^{89} concentration in new material incorporated in bone, milk being the main source.
(B) Apparent concentration s(τ) of Sr^{89} if milk is the main source from the start of calcification.
(C) Same, corrected for placental discrimination and lower concentration in mother's milk
mean marrow dose
mrem/year
10
5
0.5
1.0
1.5
2.0
years
τ
BIRTH

Possible biological consequences of nuclear weapon tests

109. Using the dose-effect constants and the calculated dose commitments per year of injection, it is possible to compute the number of seriously affected persons in the world's population. These numbers cannot be said to represent the expected result, not even the likely one, as no level of likelihood can be associated with the assumptions made. However, they are numbers that cannot be ruled out on the basis of present knowledge, and they follow from the assumptions made in this text. Table VIII gives the biological commitments per year of injection.

110. The total consequences in the form of the number of cases over all years subsequent to one year of injection of fission products to the stratosphere have, in the case of the assumption of a non-threshold, linear dose-effect relation, been calculated from the following formulas which summarize the preceding computations.

For the number of major genetic effects

$$N = K_g \cdot P \cdot D^1_{\infty} = K_g \cdot P \cdot \left[g_i \cdot F_r(\infty) + g_e \cdot F_d(\infty) + D^1_{trop} \right] \qquad (71)$$

where D^1_{trop} is the annual gonad dose from tropospheric fall-out and the other symbols are the ones used in the preceding text.

For the number of leukemia cases

$$N = K_l \cdot P \cdot D^1_{\infty} = K_l \cdot P \cdot \overline{F}_m \cdot \gamma \cdot a \cdot F_d(\infty) \qquad (72)$$

111. The world population has been taken to be $P = 5 \cdot 10^9$ in the genetic case and $P = 3 \cdot 10^9$ in the somatic case.

112. The total number of cases has not been calculated in Annex D and is not given elsewhere in the report of the Committee. The result presented in table VIII does not imply any other differences from the assumptions stated in Annex D than the ones reflected by the factors in the formulas (71) and (72).

113. Annual number of cases has been estimated in Annex D but cannot be derived by the approach used here. As the values of the 30-year gonad dose and 70-year marrow dose as calculated here do not differ appreciably from the values calculated in Annex D, the more conservative approximate calculations in that Annex yield a result that is not far from the one derived here.

/...

114. The number of cases under the assumption of a threshold in the dose-effect relation can only be estimated from the number of individuals that would have a dose exceeding the threshold dose because of the total exposure produced by all sources of radiation. The number of cases of injury would be much less than the number of persons exceeding the threshold. The 70-year marrow doses, as shown in table VII, may not be relevant in the threshold case but may have to be multiplied by a non-uniform distribution factor that is of the order of 10 for chronic Sr^{90} poisoning. The population-weighted averages do not apply either, and the local values of the geographic factor G_i must replace $\overline{G}$.

Table VII. Maximum 70-year mean marrow doses

(A) For a milk diet

Tests cease at end of		Assumption (a)		Assumption (b)	
		D_{70}(mrem)	% of equilibrium	D_{70}(mrem)	% of equilibrium
T = 0	1958	83	17	83	7
10	1968	150	30	235	21
20	1978	205	41	375	33
30	1988	255	51	495	44
∞	-	500	100	1,130	100

(B) For a rice diet

Tests cease at end of		Assumption (a)		Assumption (b)	
		D_{70}(mrem)	% of equilibrium	D_{70}(mrem)	% of equilibrium
T = 0	1958	500	17	500	8
10	1968	900	30	1,420	21
20	1978	1,250	41	2,250	33
30	1988	1,550	51	3,000	44
∞	-	3,000	100	6,760	100

Table VIII

Estimate of certain possible total genetic and leukemogenic consequences of radiation received by the world population

(To facilitate numerical checks, the numbers in the table have not been rounded off to a degree that would reflect the uncertainty involved)	Total, following one year of exposure to natural radiation	Total, following one year of nuclear test explosions --	
		Continued on assumption (a)*	Continued on assumption (b)* **
Leukemia (on basis of the assumption that no threshold exists):			
Number of cases for			
(1) a milk diet	6,800	365	820
(2) a rice diet	6,800	2,190	4,920
(on basis of the threshold assumption, see paragraph 114)			
Major genetic effects /			
Number of cases if the doubling dose is 100 rem and the current fraction of affected births is 1 per cent	21,500	560	1,140
Number of cases if the doubling dose is 10 rem and the current fraction of affected births is 4 per cent	860,000	22,400	45,600

* See paragraph 19.

** This would also apply to the years in the period 1954-1958.

/ The dose contribution from C^{14} produced by nuclear test explosions has not been included, as the dose is delivered over a much more extended period of time than that from Cs^{137} (see paragraph 59).

REFERENCES

1. Stewart, N.G., Crooks, R.N., and Fisher, E.M.R.: The radiological dose to persons in the U.K. due to the debris from nuclear test explosions prior to January 1956. A/AC.82/G/R.20.

2. Libby, W.F.: Radioactive strontium fallout. Proc. Natl. Acad. Sci. (U.S.), 42, 365-390 (1956), and A/AC.82/G/R.131.

3. Communicated by L. Machta, representative of the World Meteorological Organization to the United Nations Scientific Committee on the Effects of Atomic Radiation, 1958.

4. Marley, W.G.: The long-range fall-out from nuclear test explosions. Medical Research Council (U.K.): The hazard to man of nuclear and allied radiations, London (1956), p. 121-125. A/AC.82/G/R.172.

5. Miyaka, Y., Sugiura, Y., Saruhashi, K., and Kanazawa, T.: The estimation of the amount of Sr-90 deposition and the external infinite gamma dose in Japan due to man-made radioactivity. A/AC.82/G/R.2.

6. Alba A., F., Brody, T.A., Cameras, R., Palacicos, A., Rickards C., G., Tejera R., A., and de Velarde, E.G.B.: Third report on the studies of radioactive fall-out. A/AC.82/G/R.164.

7. Blok, J.: Radioactive fall-out measurements in the Netherlands until December 31, 1957. A/AC.82/G/R.184.

8. Anderson, E.C., Schuch, R.L., Fisher, W.R., and Langham, W.: Radioactivity of people and foods. Science 125, 1273-1278 (1957), and A/AC.82/G/R.123.

9. Rundo, J.: Measurement of ^{137}Cs in human beings in the United Kingdom 1956/57 A/AC.82/G/R.167.

10. Rafter, T.A. and Fergusson, G.J.: The atom bomb effect. Recent increase in the ^{14}C content of the atmosphere, biosphere, and surface waters of the oceans New Zealand J. of Sci. and Tech., Sect. B., 38, 871-883 (1957).

11. de Vries, H.: "Atom bomb effect". The natural activity of radiocarbon in plants, shells and snails in the past four years. Science, 128, 250-251 (1958).

12. Fergusson, G.J.: Reduction of atmospheric radiocarbon concentration by fossile fuel carbon dioxide and the mean life of carbon dioxide in the atmosphere. Proc. Roy. Soc. (London), 243, 561-574 (1958).

13. Communicated by R. Björnerstedt and A. Engström, 1958.

14. Communicated by F.W. Spiers, 1958.

15. Court-Brown, W.M. and Doll, R.: Radiation and leukaemia. Lancet 1, 162-163 (1958).

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16. Wald, N.: Leukemia in Hiroshima City atomic bomb survivors. Science 127, 699-700 (1958).

17. Mitchell, H.H., Hamilton, T.S., Steggerda, F.R., and Bean, H.W.: The chemical composition of the adult human body and its bearing on the biochemistry of growth. J. Biol. Chem. 158, 625-637 (1945).

18. Bronner, F. and Harris, R.S.: Absorption and metabolism of calcium in human beings, studied with calcium-45. Ann. New York Acad. Sci., 64, 314-325 (1956).

19. Bauer, G.C.H., Carlsson, A., and Lindquist, B.: Bone salt metabolism in humans studied by means of radiocalcium. Acta medica Scandinavica 158, 143-150 (1957).

20. Bauer, G.C.H. and Ray, R.D.: Kinetics of bone surgery in man. J. of Bone and Joint Surgery, 40-A., 171-186 (1958).

21. Bronner, F., Benda, C.E., Harris, R.S., and Kreplick, J.: Calcium metabolism in a case of gargoylism, studied with the aid of radiocalcium. J. Clinical Investigation 37, 139-147 (1958).

22. Grummitt, W.E. and Mar, P.G.: Levels of strontium-90 in Canada in 1957. Atomic Energy of Canada Limited and Department of National Health and Welfare Report CRC 786 (1958).
