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THE HALF-TIME OF CESIUM-137 IN MAN[1]

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As part of participation in the Federal Radiation Council Working Group and *Ad Hoc* Panel on Strontium and Cesium Radionuclides that developed Report No. 7, the available material and data on the half-time of cesium-137 in man were reviewed. The purpose of this effort was to collect data on measured values of cesium-137 half-time that could be employed, together with other material, to support the use of an assumed value of biological half-life in whole body and bone marrow dose calculations.

This report represents (1) collected data on measured values of cesium-137 half-time in man, (2) a suggested model for expressing cesium-137 half-time as a function of age, and (3) estimates of doses and body burdens for a unit intake of cesium-137 and for intake of cesium-137 in milk, using an assumed pattern of milk consumption by various ages.

An important consideration in determining whole body and bone marrow radiation dose to an exposed population from internal cesium-137 is the effective half-time of this radionuclide in man. Should there be a different biological half-time for cesium-137 in various age groups within a population and an effective half-time[3] which varies as a function of age, it will be necessary to consider this factor in determining doses to the population and in determining which age group in the population will receive the highest exposure from a contaminating event.

Available data

Table 1 lists data from the literature. The symbol T_b will be used to represent the biological half-time of cesium-137 in man. Where possible, the range of observed values for each group of individuals studied is included.

Discussion of data

Rather than present individual measurements of T_b for each subject, many investigators have reported an average value with an indication of the range of observed values. Considering the lower limits of the range of values for "adults" (unweighted for number of subjects) for all investigators where a range was given, the average value for the lower limits is about 78 days. The average value for the upper limits is about 122 days, and the overall average is about 98 days for these data.

The unweighted mean of the "Body Radioactivity Measurements and Excretion or Dietary Analysis" data from Rundo's summary is 110 days. The "Body Radioactivity Measurements" give an unweighted mean of 108 days. The "Excretion or Dietary Analysis" data give an unweighted mean of 114 days. Thus, the two techniques appear to give results which are in close agreement.

The data collected on T_b for groups of subjects are presented graphically in figure 1. Also plotted are individual values for 6- and 8-year-old girls and for two infants (Rundo), and values for three young women and two infants (Bengtsson *et al.*). In order to display the data for "adults", it has been assumed that this age group consists of those about 20 to 25 years of age and older, and the elderly are assumed to be over 60 years of age.

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[1] Adapted from HASL-164:281-300, Clearinghouse for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151 (October 1, 1965). Price $7.00.

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[3] For cesium-137 in man, the radiological half-time is so long (about 11,000 days) and the biological half-time is so short (of the order of 100 days or less) that for purposes of this report, the effective half-time can be considered equal to the biological half-time.

Table 1. Cesium-137 half-time [illegible] from the literature

Group	Age (years)	T_b (days)	Range (days)[a]	Reference
1 girl	6	24	—	(1)
1 girl	4	39	—	(1)
[illegible]	16	50	—	(1)
[illegible]	all ages	105	std. deviation 35%	(1)
[illegible]	adults	74	—	(2)
[illegible]	[illegible]-22	66	—	(2)
[illegible]	26-75	64	±10	(2)
[illegible]	7-76	65.5	±10	(2)
[illegible]	0-14	44	+10 −5	(2)
[illegible]	adults	100	—	(3)
[illegible]	30-40	81	48 in summer 119 in winter	(4)
[illegible] children	~15	½ the value for adults.	—	(4)
Marshallese people		70	—	(5)
10	normal subjects	[b] 1	0.8-1.2	(6)
		[c] 89	58-129	(6)
[illegible]	men	—	109-149	(6)
[illegible]	adult	53 (in 1959) 56 (in 1961)		(6)
1	adult	94	—	(6)
1	adult	136	—	(6)
average value		110	—	(7)
average value		140	—	(8)
2	adults	[d] 110	—	(9)
[illegible]	adults	[d] 115	110-119	(9)
1	adult	[d] 74	—	(9)
[illegible]	adult	[d] 144	—	(9)
[illegible]	adults	[d] 60	57-63	(9)
[illegible]	adults	[d] 135	110-147	(9)
[illegible]	adult	[d] 150	—	(9)
[illegible]	adults	[d] 122	109-148	(9)
[illegible]	adults	[d] 75	54-114	(9)
[illegible]	adults	[d] 109	79-123	(9)
[illegible]	adults	[d] 89	58-129	(9)
[illegible]	adults	[e] 145	—	(9)
[illegible]	adults	[e] 125	92-157	(9)
[illegible]	adult	[e] 188	—	(9)
[illegible]	adults	[e] 110	—	(9)
[illegible]	adults	[e] 56	53-60	(9)
[illegible]	adults	[e] 98	86-112	(9)
[illegible]	adults	[e] 170	140-200	(9)
3	adults	[e] 97	53-140	(9)
[illegible]	adult	[e] 71	—	(9)
10	adults	[e] 76	—	(9)
3	adults	99	76-126	(10)
1	adult	81	—	(11)
1	adult	95	—	(11)
1 woman-IS	22	69	±4	(12)
		65	[f] ±5	(12)
1 woman	26	73	±10	(12)
1 woman-EB	23	32	±2	(12)
1 infant of IS	12 days	21	±5	(12)
1 infant of EB	2 days	25	±3	(12)
1 infant	early infancy	9.6	—	(13)
1 infant	early infancy	6.6	—	(13)
12	adults	91	±18	(14)
1 infant	17 days	13	—	(15)
1 infant	24 days	33	—	(15)
1 infant	36 days	21	—	(15)
1 infant	56 days	18	—	(15)
1 infant	43 days	12	—	(15)
1 child	[illegible]	29	—	(15)
1 child	5	43	—	(15)
1 child	9	40	—	(15)
1 adult	21	108	—	(15)
1 adult	[illegible]	100	—	(15)
1 adult	[illegible]	77	—	(15)
1 adult	[illegible]	76	—	(15)
1 adult	33	101	—	(15)
1 adult	33	121	—	(15)
1 adult	35	131	—	(15)
1 adult	33	94	—	(15)
1 adult	35	108	—	(15)
1 adult	46	84	—	(15)
1 adult	49	136	—	(15)
1 adult	51	73	—	(15)
1 adult	52	101	—	(15)
2	elderly women	[g] 3.2	±2.0	(16)
		[h] 57	±17	(16)
2	elderly men	[g] 2.2	±1.4	(16)
		[h] 69	±16	(16)

[a] The uncertainty in the measurement is given, when available, where data are presented for one subject.
[b] Small fraction eliminated
[c] Major fraction eliminated
[d] Body radioactivity measurement
[e] Excretion or dietary analysis
[f] Two months later
[g] Fast component
[h] Slow component

From table 1 and from figure 1, it is seen that much of the data on T_b are for "adults",

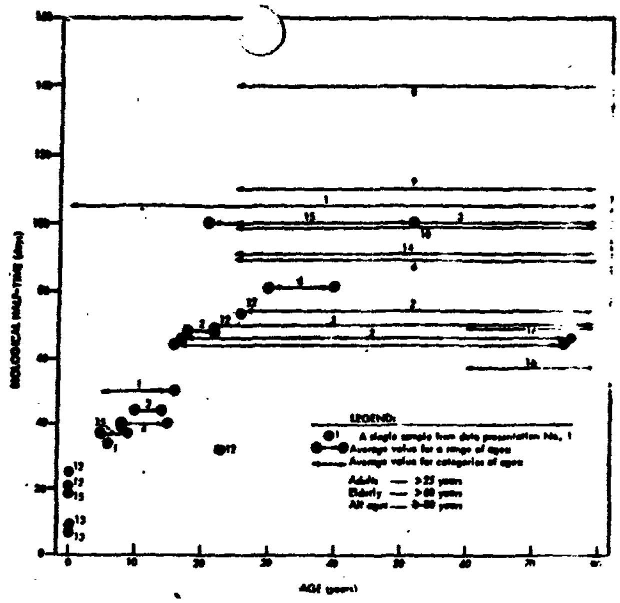

Figure 1. Biological half-time versus age

and that investigators have reported half-times, for adult groups, of about one day for a small fraction of the cesium-137 intake (about 10 percent) and values between about 60 and 180 days for the major portion of the intak[e]. While part of the difference in values from various investigators may lie in the realm of factors of instrumentation, calibration, laboratory technique, etc., the measured values generally appear to represent real differences among individuals. The range of values obtained by a single investigator for a group of subjects must involve many biological and environmental factors for which there is littl[e] information. No attempt will be made to identify these factors except for the possible influence of age on the biological half-time of cesium-137 in man (age may be an indirect factor).

The data are meager, but figure 1 suggest[s] that the value of T_b for those groups und[er] about 20 to 25 years of age decreases with a[ge] and that T_b may be as low as 6 to 7 da[ys] for infants a few days old. For the four infant[s] in figure 1, the average value is about 15 days which agrees with Pendleton's average of 1[9] days for five infants.

One additional feature in the data is possibl[y] significant. For the age groups reported, [no] investigator (from the available reports) ha[s] reported a value of T_b greater than 70 days f[or] *groups* under 25 years of age or a value l[ess] than about 50 to 60 days for *groups* over [25] years of age.

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Guarded statements by s( ) investigators indicate reservation in specifying trends in the data, such as relationships between T_b and age, sex, or species. Rundo has said, "If there is a change of half-life with age then it presumably starts at birth and increases steadily until adulthood is reached" (*1*). Other investigators indicate a stronger support for a relationship between T_b and age. Bengtsson *et al.* state "The results also confirm that biological half-time for cesium increases with age" (*12*). Onstead *et al.* report that in their studies involving more than 6,000 individuals, ". . . our findings suggest that, within a single species, biological half-life is dependent on age" (*17*).

In referencing the use of 100 days for the biological half-life of cesium in man, the December 1964 report to the Federal Radiation Council by the National Academy of Sciences Advisory Committee, entitled "Implications to Man of Irradiation by Internally Deposited Strontium–89, Strontium–90, and Cesium–137" (*18*) contains the following:

> "This value is almost certainly too large for children, perhaps by a factor of three to five."

The Federal Radiation Council, in its Report No. 7, (*19*) stated:

> "The data for persons younger than 25 years suggest that the biological half-life before maturity may be a function of age. Biological half-lives of about 20 days or less have been reported for infants. For this report a value of 30 days is used as the biological half-life of cesium–137 in infants."

A value of 30 days for infants appears to be a conservative assumption since the available data for infants show values close to, but below, this value.

Boni's value of 81 days, which is applicable for adults 20 to 40 years of age, is in close agreement with the average value of the lower limit for adults for all investigators of 78 days. However, there are little data for ages within the category specified as "adults" to determine if there is a trend of change in T_b as a function of age above about 25 years. The average value for adults for all investigators, those that specified a range of values and those that did not, is 101 days. The most data for an early study for all ages in a population group are for the Marshallese peo( ) with a value of 70 days reported (*5*).

The data of Miettinen suggest an average value of about 70 days for the ages 16 through 75 years. Lists of "age limits" indicate most of these individuals were less than 50 years of age. Whether the inclusion of individuals of ages down to 16 years has the effect of lowering the average value of T_b for these groups compared to data on groups of "adults" presented by Rundo and Hansen and others, is not known. Possibly other biological and environmental factors are more important.

Model development

Considering the available values of T_b for the entire range of ages in the population, the trend that is suggested for T_b and age may be presented graphically. The solid line in figure 2 is drawn to account for the apparent rapid change of T_b with age for those less than about 25 years of age, to provide an average value of about 80 days for younger adults as suggested by Boni's measurements, and to provide an average value for adults over 25 years of age of about 100 days. Considering all age groups, the solid line in figure 2 develops an average T_b for all ages of about 75 days.

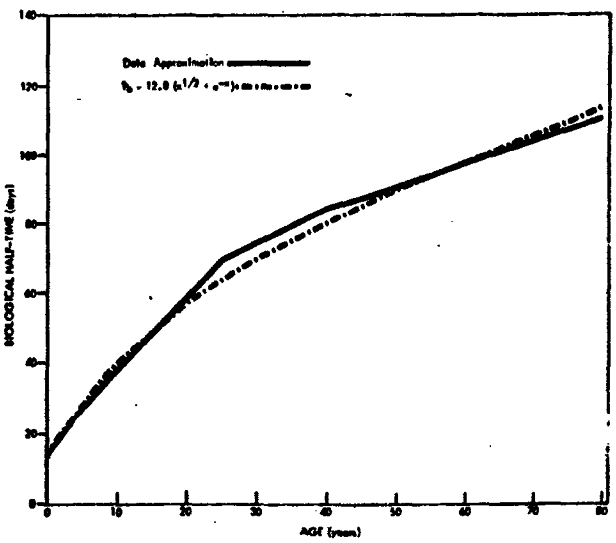

Figure 2. Biological half-time versus age

The three segments of figure 2 may be approximated by:

$$T_b = 12.8\,(x^{1} + e^{-x}) \qquad (1)$$

where:

T_b = biological half life (years)
x = age (years)

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The dotted curve in figure 1 shows that the fit is good for all ages. While this expression does not provide for estimating effective half-times of cesium–137 for individuals, it does provide a close approximation to averages of measured values of cesium–137 retention for groups of subjects.

Equation (1) may be combined with the equation in FRC Report No. 7 (*19*) that relates dose to whole body and bone marrow in rads to intake of cesium–137 to form a generalized expression that includes the age of various groups within an exposed population:

$$D = \frac{I_t}{W} \times 0.03 \times 1.44\ [12.8\ (x^{\frac{1}{2}} + e^{-x})]$$

$$D = \frac{0.55\ I_t\ (x^{\frac{1}{2}} + e^{-x})}{W} \qquad (2)$$

where:

D = total dose (rads)
I_t = total intake of ^{137}Cs (microcuries)
W = body weight (kilograms)
x = age of exposed group (years)

This equation applies where it can be assumed that body weight, W, does not change significantly during exposure.

If the intake of concern is through the dietary pathway of pasture-cow-milk-man, the total intake of cesium–137 for an acute contaminating event can be expressed in terms of the maximum daily intake. (See "Estimates of the Concentration of Strontium–89, Strontium–90, and Cesium–137 in Milk as a Function of Time", Report of Special *Ad Hoc* Committee of Federal Radiation Council, *Radiological Health Data*, July 1965.

$$I_t \sim 32\ I_m \qquad (3)$$

where:

I_m = maximum daily intake of $^{137}C_s$

For the case of a single acute deposition of cesium–137 on pasturage, the total dose may be estimated from:

$$D = \frac{17.6\ I_m\ (x^{\frac{1}{2}} + e^{-x})}{W} \qquad (4)$$

For those less than about 10 years of age, most of this dose will have been received within about 1 year.

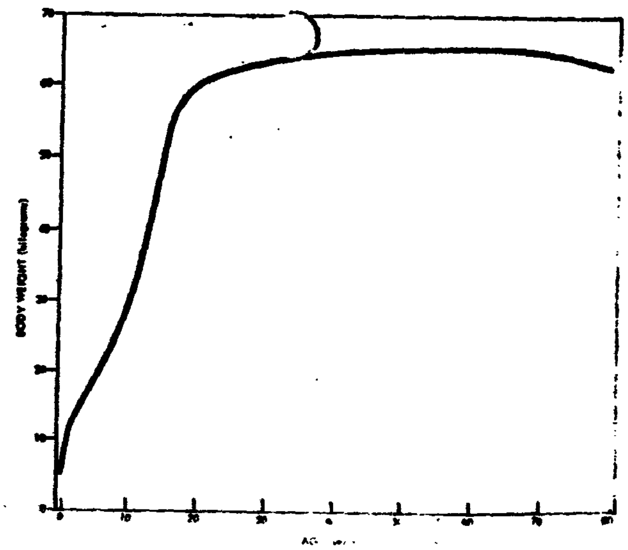

Figure 3. Body weight versus age (average for male and female)

Model application—dose estimates

Figure 3 gives the average male and female body weights in kilograms from birth to 80 years. The average values of body weight for various ages are generally not the same for male and female; however, the differences in weight are not large. For these body weights and using the generalized expression for dose, figure 4 presents the total whole body and bone marrow dose as a function of age for a total intake of 1.0 microcurie of cesium–137. The doses in figure 4 would also be obtained using equation (4) and a maximum daily cesium–137 intake in milk of $^1/_{32}$ microcurie or 31 nanocuries from an acute deposition of cesium–137.

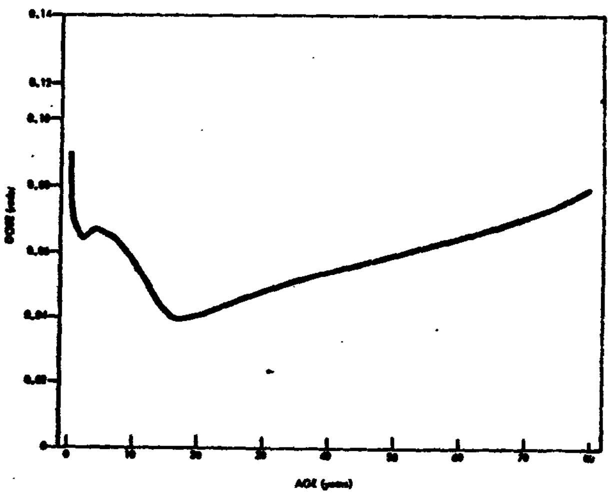

Figure 4. Total whole body and bone marrow dose from internal cesium–137 versus age (an assumed total intake of 1 μCi ^{137}Cs)

Figure 4 indicates that with the use of this model for biological half-ti..., the highest and lowest doses for all ages from a given intake of cesium–137 differ by a factor of about two. This occurs even though body weights vary by a factor of about 20, and biological half-times vary by a factor of about 10. For the younger ages, those less than 1 year of age receive the highest dose. Those 70 to 80 years of age may receive a comparable dose. However, definitive data for ages greater than 50 are not available and the model suggested may not be really representative for ages over 50 years.

Again, if one assumes that the dietary item of interest is whole milk, the doses in figure 4 can be modified by a pattern of intake for milk. Table 2 presents data on average at-home milk consumption as a function of age. Values of average consumption in table 2 were developed from a percentage distribution of milk intake by age (*Radiological Health Data,* January 1963). This study of at-home milk consumption was conducted throughout the United States in July 1962. Since the study did not include consumption of whole milk outside the home, consumption may be underestimated for those ages consuming whole milk away from home. Table 2 also presents the average consumption by each age group relative to consumption by males less than 1 year of age (the intake normalization factor). The average consumption for males less than one year of age is seen to be 17.8 ounces per day. This is approximately one-half liter per day (16.9 oz/day).

Table 2. Average daily fresh whole milk consumption at home in U.S.[a]

Age (years)	Average consumption (fluid ounces)		No consumption (percent)	Normalization factor consumption/<1 year male consumption	
	Male	Female		Male	Female
<1	17.8	16.3	38.0	1.0	.92
1–4	17.8	16.9	15.9	1.0	.95
5–9	16.6	14.5	20.5	.93	.81
10–14	16.9	12.7	25.0	.95	.72
15–19	16.3	10.2	28.9	.92	.58
20–24	11.8	7.5	35.1	.66	.42
25–29	9.8	6.8	39.1	.55	.38
30–34	8.7	5.7	37.5	.49	.32
35–44	8.3	5.7	39.1	.47	.32
45–54	7.6	5.4	42.0	.43	.31
55–64	8.1	5.9	40.9	.45	.33
>65	8.6	6.8	35.4	.48	.38

[a] Average consumption values and normalization factors developed from report on "National Food Consumption Survey" in Radiological Health Data, Vol IV, No. 1, January 1963.

The doses in figure 4, averaged for each age group, have been modified by the normalization factors in table 2 to illustrate the effects that a pattern of milk consumption may have on dose. The result... shown in figure 5.

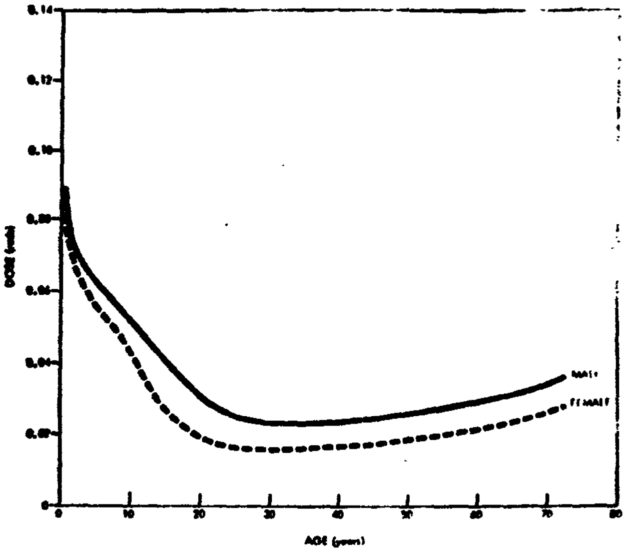

Figure 5. Total whole body and bone marrow dose from internal cesium–137 versus age (an assumed pattern of dietary intake of cesium–137 in milk for males less than 1 year of age consuming 1 μCi)

The influence of the pattern of milk consumption in table 2 is to reduce the average doses for most ages relative to the doses in figure 4.

The sex-related differences in milk consumption cause males to receive higher average doses than females for all ages. The difference in dose between ages receiving the highest and lowest values is a factor of about four for male and about five for female, and males less than 1 year of age receive the highest dose.

The yearly dose that would be received by various age *groups* from a continuing daily intake of cesium–137 may be estimated by determining the average cesium–137 body burden during the year and using the following:

$$D_r = \frac{B/W}{85.7} \qquad (5)$$

where:

D_r = dose rate (rads per year)
B = average body burden (nanocuries)
and W = body weight (kilograms)

The determination of average body burden for a continuing intake of cesium–137 is described in the following section (see equation (9) and figure 7).

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Model application—body bu   n estimates

For acute ingestion of cesium-137 (ingestion over a period of a few days), estimated average body burdens can be determined as a function of time after ingestion for the exposed population from:

$$B_t = \frac{B_o}{1000} e^{-.693\ t/T_b} \qquad (6)$$

where

B_t = body burdens (nanocuries)
B_o = initial body burden,
= total intake in picocuries assuming 100 percent absorption,
t = time after ingestion (days),
T_b = biological half-time (days),
= 12.8 $(x^{\frac{1}{2}}+e^{-x})$

where x = age (years).

Conversely for acute ingestion, the total intake can be estimated for various age groups if average body burdens are known at some time after ingestion.

For ingestion of cesium-137 that decreases with time, average body burdens within the population may be estimated as a function of time from:

$$B_t = \frac{R_o}{1000\ (\lambda_i - \lambda_b)} (e^{-\lambda bt} - e^{-\lambda it}) \qquad (7)$$

where

R_o = initial rate of intake (picocuries per day),
λ_b = biological decay constant
= .693/12.8$(x^{\frac{1}{2}}+e^{-x})$,
λ_i = intake decay constant = .693/T_i,
T_i = half-time for intake after maximum concentration (days)

FRC Report No. 7 (*19*) indicates that for an acute deposition on pasturage, the total cesium-137 intake from milk may be 32 times the intake on the day of the maximum concentration in milk (assuming the same amount of milk is consumed each day). The portion of the total intake occurring prior to maximum concentration is about 16 percent of the total intake. The intake occurring after maximum concentration is about 27 times the maximum. Therefore, 27 days may be considered the mean time of cesium-137 in milk following maximum concentration. The half-time for intake after maximum concentration is:

$$T_i = 27 \times 0.693 \sim 18 \text{ days.}$$

For acute deposition of cesium-137 on pasturage utilized by dairy cows, it has been estimated that the maximum concentration in milk will occur about 6 days following deposition. The average body burden for various ages resulting from such changing levels in milk may be approximated by:

1. Assuming total milk intake prior to maximum concentration is an acute intake using equation (6).
2. Assuming an additional intake using the maximum daily intake as R_o in equation (7).

The estimated body burden from milk consumption will be the burden from equation (6), plus the burden from equation (7). Contributions to total body burden from other contaminated foods will be additive. Figure 6 presents the body burden for males 1 year of age, for an acute deposition on pasturage, where the maximum concentration of cesium-137 in milk reached a level of 2,000 pCi/liter. Figure 6 indicates that maximum burden will be reached in about 25 days for this age group.

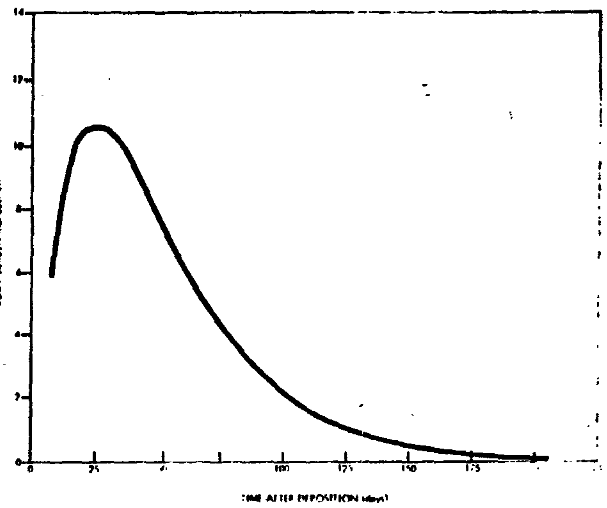

Figure 6. Cesium-137 body burden for males less than 1 year of age versus time after acute deposition (assuming maximum milk concentration reaches 2,000 pCi/liter)

Other assumptions regarding the pattern of milk consumption versus age may apply for various portions of the U.S. population. Body burdens for the milk consumption pattern in table 1 may be underestimated for the ages consuming quantities of milk away from home.

For a continuing intake of cesium-137 (intake that occurs over a period of years), estimates of average body burdens within a population can be developed from the following:

$$B = R\,T_m A_f/1000 \qquad (8)$$

where:

B = body burden (nanocuries)
R = rate of intake of ^{137}Cs (picocuries per day)
T_m = biological mean time (days),
A_f = absorption factor, assumed to be 1.0.

With biological mean time expressed as a function of age, equation (8) becomes:

$$B = 0.018\,R\,(x^{1} + e^{-x}) \qquad (9)$$

where:

x = age (years)

Equation (9) may be used, for example, to estimate the average body burdens of cesium-137 in the U.S. population from milk consumption. The U.S. Public Health Service pasteurized milk network results for 1963 and 1964 averaged 114 and 109 pCi/liter, respectively (*20, 21*).

These data indicate that the average level of cesium-137 in U.S. milk supplies has decreased slowly over the past 2 years. Considering the small change in these levels, it can be assumed that the various age groups in the population are in equilibrium with the cesium-137 levels in milk they consume for the portion of their body burden due to milk intake, and their average body burdens for 1964 may be determined from an average value of daily cesium-137 intake.

If it is assumed that milk ingestion for males less than 1 year of age resulted in an average intake of 55 pCi/day during 1964, and using the normalization factors in table 2 to estimate milk consumption by other age groups in the population, estimated body burdens may be determined from equation (9). The resulting values are shown in figure 7.

The dose to males less than 1 year of age from at-home milk consumption, using equation (5), is about 0.002 rad or 2.0 millirads in 1964. The point should be stressed that these estimates apply only to that portion of the cesium-137 body burdens of the U.S. population due to milk consumption at home. The contribution to body burden and whole body dose from milk consumption outside the home and from other items of the diet are additive.

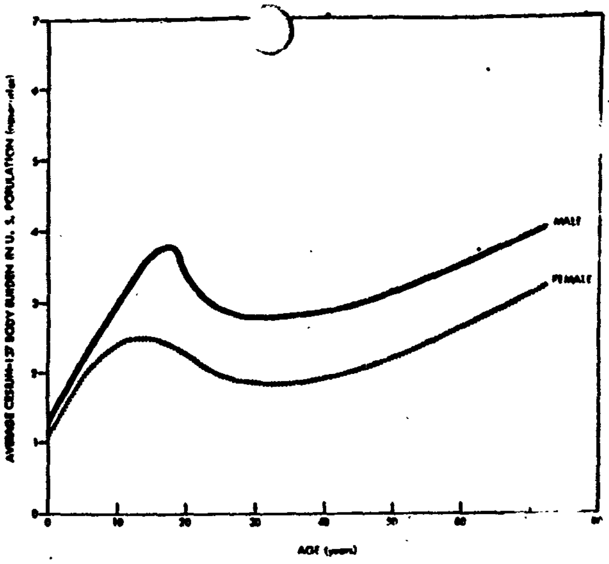

Figure 7. Estimated cesium-137 body burdens from milk consumption for U.S. population in 1964

For cesium-137 in U.S. milk supplies, estimates of cesium-137 body burden in figure 7 indicate that males 15 to 20 years of age had the highest levels; those less than 1 year of age, male and female, had the lowest levels; and females of all ages had a lower average level than males of the same age.

Summary

The observations of biological half-time for cesium-137 in man indicate that half-time is a function of age. The average biological half-times for cesium-137 from birth through adult life vary by a factor of about 10. A simple mathematical expression has been presented which relates half-time of retention of cesium-137 and age. Though the model is crude, it has utility in predictions of doses and body burdens from cesium-137 for various ages within an exposed population. Additional measurements of cesium-137 retention are needed, particularly for younger age groups, to further refine the model and to improve prediction capability. More data are also needed for the elderly.

The combination of changes in half-time and body weight results in a dose variation, for a given cesium-137 intake, from birth through adult life, of a factor of about two. The addition of assumptions regarding patterns of milk intake as a function of age and resultant cesium-137 intake leads to a different distribution of dose with age than is found for a fixed intake for all ages. For the assumed p[illegible]rn of intake of cesium-137 in milk, the dose varies within the range of ages from birth through adult life by a factor of four to five, with males less than 1 year of age receiving the highest dose.

[illegible] acute contaminating event, the time [illegible] maximum cesium-137 body burden is a function of age. Maximum body burdens from milk consumption may occur in about 25 days after an acute contaminating event for those expected to receive the highest dose; *i.e.*, those less than 1 year of age.

It is estimated that for a long-term, slowly changing intake of cesium-137, such as occurred from use of fresh whole milk supplies by the U.S. population in 1964, males 15 to 20 [illegible] of age had the highest body burdens; [illegible] less than 1 year of age, male and female, [illegible] lowest body burdens; and females of [illegible] had lower body burdens than males of [illegible] age.

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