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Health & Biology

INTERNAL DOSE DETERMINATIONS OF SEVERAL RADIOISOTOPES

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HEALTH PHYSICS DIVISION

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by

Charles H. Perry

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INTERNAL DOSE DETERMINATIONS OF SEVERAL RADIOISOTOPES

Part I

Radioisotopes of Those Elements Which Are
Common to Our Body Metabolism

Part II

Insoluble and Soluble Compounds of Uranium
Isotopes (U^{234}, U^{235}, U^{238})

by

Charles H. Perry

PART I

RADIOISOTOPES OF THOSE ELEMENTS WHICH ARE COMMON TO OUR BODY METABOLISM

A. Introduction

The tissue doses produced by the radioisotopes of those elements which are common to our body metabolism may be calculated in a more or less simplified manner if we consider the radioisotopes as being in equilibrium with the stable elements within the organs. However, in those cases where it is desired to control the magnitudes of the tissue doses at a time less than about five effective half-lives after the beginning of the exposure, all that is required is to retain the factor $(1 - e^{-\lambda t})^{-1}$ in the calculations. All calculations have been made herein on the basis that $t \geq 5T$ which permits of the omission of the factor $(1 - e^{-\lambda t})^{-1}$.

Little is known concerning the exact distribution of a given element within an organ. Without this essential information it becomes necessary to use an average concentration value and to introduce either a factor which represents a good guess concerning the degree of non-uniformity of distribution, or to use a factor of safety which includes this as well as other unknown quantities. The latter procedure was chosen for purposes of simplicity. It is suggested, however, that if and when experimental data are available which supply this much needed information, proper factors be introduced in the equations here developed to produce more realistic values.

The factors of safety listed in Table III are suggested values only. It will be noted that for all radioelements, except radioiodine, a factor of safety of 10^{-2} has been suggested. In the case of radioiodine a factor of safety of 10^{-1} has been suggested. There are many factors which should govern the selection of a value for the factor of safety. Among these are the degree of uncertainty which enters into the various assumptions and calculations of the tissue doses, and the degree of risk which is involved. Much can be said concerning the degree of risk. Suffice to say, however, that there is a vast difference between the permissible risks to the workers in non-controlled areas (cities), controlled areas (AEC installations, etc.), and lastly the risk which the men in the armed services are prepared to take. It is suggested that the factor of safety which is selected be fitted to the risk at hand and to the degree of uncertainty.

The daily intakes of hydrogen and of carbon were calculated on the basis of a 3000 calorie intake per day. In this calculation, a daily intake of 130.4 grams of protein, 130.4 grams of fat, and 326 grams of carbohydrate were assumed. It is very difficult to choose values which are acceptable to all because while one group recommends a low protein intake, another will recommend a high protein intake. The above figures are in-between and were extrapolated from "Rankes" diet published in the "Textbook of Physiology" by Zoetout and Tuttle. In the case of the hydrogen intake, 2200 ml water were added to the daily intake as a source of hydrogen.

The daily intakes for the other elements were selected on an average basis from several published works. It is a simple matter to substitute different values for the element intakes in the equations for tissue dose. It is suggested that this substitution be done when advisable.

Experimental data concerning the biological decay constants of the elements in the various organs are not available. It becomes necessary therefore to make approximations which are based upon assumptions.

Although not factual, it has been customary to consider the biological decay constant as being exponential in character. This assumption makes it possible to obtain the effective decay constant by simply adding the biological and radiological decay constants together. This procedure has been followed herein.

It has been further assumed that the biological decay for any given element within a given organ is directly proportional to the quantity of the element with the organ. This may or may not be a close approximation; however, it has been used here because of the lack of experimental data.

The quantities f_1 in the table, which are the fractions of elements which enter the blood either via the lungs or the gastro-intestinal tract, are assumed. In the case where the entry is via the lungs it is assumed that 75% of all the radioactive dust which is breathed will reach the blood. This percentage may seem high; however, it not only includes the maximum fraction which can enter the blood via the alveoli ($\sim 2/3$) but also that portion of the dust which is deposited in the upper respiratory tract and subsequently swallowed, thus reaching the blood via the gastro-intentinal tract.

The fraction f_1 which enters the blood via the G-I tract is assumed to be 1. Although, in some cases the value might be closer to 0.5, the value has been set as 1 for three reasons. First, the elements considered here are common to the body metabolism and therefore they are expected to be readily absorbed by the G-I tract tissues, thus entering the blood stream. Second, it is a safe assumption. And third, it is very easy to replace the figure one with a more factual figure based upon experimentation if and when these data are available.

The factor f_2, which is that fraction of the element which enters the organ from the blood, is assumed. Because of the absence of experimental data for these elements, it is assumed that the fractional elemental intake to the organ is equal to the fractional elemental content of the organ. That is, f_2, is equal to the ratio of the weight of the element in the organ to the weight of the element in the body. It is pointed out here that in some cases this may not be even a close approximation. Further, the element turnover rate may vary considerably in different portions of the same organ.

The other assumptions such as the volumes of air breathed and the quantity of water consumed during given periods of time are arbitrary; however, the values used are in agreement with the recommendations made, and agreed upon, at the "Chalk River" meeting.*

All calculations for air and water concentrations were made on the basis that the dose rate dr/dt to tissue is .3 rep/week or .3/7 rep per day. For some purposes it will be desira ble to choose other dose rates.

B. Derivation of Equations

Development of Equation for P.D. μc/day (Permissible Dose/day, expressed in μc).

Let m = mass of organ in grams

Q = μc/gm organ tissue to give a dose rate of .3/7 rep/day or .3 rep/week

f = that fraction of elemental intake which gets to the organ via lungs or G-I tract

λ = total decay (elimination) constant, days^{-1}

* Meeting of the representatives of the Committees on Radiation Protection of the United States, Great Britain and Canada, held on September 29 and 30, 1949 at Chalk River, Canada.

Then

(1) $$\frac{d\,(mQ)}{dt} = (\text{P.D./day}) \times f - \lambda mQ$$

$$\frac{d\,(mQ)}{(\text{P.D./day}) \times f - \lambda mQ} = dt$$

$$-\frac{1}{\lambda} \quad \frac{d\,(-\lambda mQ)}{(\text{P.D./day}) \times f - \lambda mQ} = dt$$

$$-\frac{1}{\lambda} \ln \Big[(\text{P.D./day})\ f \times \lambda mQ \Big]_{o}^{Q} = t \Big]_{o}^{t}$$

$$-\frac{1}{\lambda} \ln \Big[(\text{P.D./day})\ f - \lambda mQ \Big] - \ln \Big[(\text{P.D./day})\ f \Big] = t$$

$$\frac{(\text{P.D./day})\ f - \lambda mQ}{(\text{P.D./day})\ f} = e^{-\lambda t}$$

$$(\text{P.D./day})\ f - \lambda mQ = (\text{P.D./day})\ f \times e^{-\lambda t}$$

$$(\text{P.D./day})\ f - (\text{P.D./day})\ f \times e^{-\lambda t} = \lambda mQ$$

$$(\text{P.D./day})\ f\ (1 - e^{-\lambda t}) = \lambda mQ$$

(2) $$\text{P.D./day} = \frac{\lambda mQ}{f\ (1 - e^{-\lambda t})}\ \mu c$$

Since we are dealing with an equilibrium state, we may assume that $(1 - e^{-\lambda t}) \approx 1$. If one is interested in computational accuracy of $\sim 97\%$, he may assume that equilibrium exists after 5 half lives.

$$1 - e^{-\lambda t} = 1 - e^{-\frac{.693}{T} t} = 1 - e^{-\frac{.693}{T} \times 5T}$$

$$= 1 - 2^{-5} \approx 0.97$$

If the time t under consideration is $< 5T$, then the factor $(1 - e^{-\lambda t})^{-1}$ should be retained.

Letting $f = f_L$ for that fraction which gets to the organ via the lungs and $f = f_G$ for that fraction which gets to the organ via the G-I tract, we have

(3) $\quad P.D./day = Q \frac{m}{f_L} \lambda \mu c$, via lungs, or

(4) $\quad P.D./day = Q \frac{m}{f_G} \lambda \mu c$, via G-I tract.

The total decay constant is,

(5) $\quad \lambda = \lambda_b + \lambda_r \text{ days}^{-1}$,

where $\lambda_b = \frac{I f_G}{mc} \text{ days}^{-1}$,

I = element intake/day in grams,

m = gms mass of organ,

c = concentration of element in organ (gms element per gm organ),

mc = gms element in organ,

f_G = that fraction of the elemental intake which reaches the organ via the G-I tract,

T_r = radiological half-life in days, and

$$\lambda_r = \frac{.693}{T_r} \text{ days}^{-1}.$$

Substituting, we have

$$\lambda = \frac{I\ f_G}{mc} + \frac{.693}{T_r} \text{ days}^{-1}$$

Note that the quantity $I\ f_G$ is the elemental intake which reaches the organ per day. In an equilibrium state this is equal to the amount which leaves the organ per day.

Equations 3 and 4 are used to calculate the P.D./day of the radioisotopes in the attached list.

Q is determined in the following manner:

(6) $$\frac{dr}{dt} =$$

$$\frac{(3.6 \times 10^4) \times Q \times E_{eff/dis} \times 10^6 \times (4.8 \times 10^{-10})(8.64 \times 10^4)}{32.5 \times 876}$$

$$\frac{dr}{dt} = 52.4\ Q \times (E_{eff/dis})$$

where 3.6×10^4 = disintegrations/sec per μc

Q = μc/gm tissue,

$E_{eff/dis}$ = effective energy in Mev per disintegration,

10^6 = ev in Mev,

4.8×10^{-10} = esu/ion pair,

8.64×10^4 = seconds in one day,

32.5 = ev required to produce one ion pair, and

$$876 = \frac{\text{relative mass stopping power for soft tissue}}{\text{density of air}}$$

$$= \frac{1.14}{.001293}$$

The selection of a value for $\frac{dr}{dt}$ will depend upon the use for which the calculation is being made, and/or the current opinion of those who establish arbitrary dose rates. In the case at hand, we desire to determine the value of Q which will give a dose rate of .3 rep/week (or $\frac{.3}{7}$ rep/day) to the selected principal organ of retention.

Equating $\frac{dr}{dt} = \frac{.3}{7}$ rep per day, we obtain:

(7) $$\frac{.3}{7} = 52.4\, QE_{eff/dis}$$

$Q = \dfrac{8.2 \times 10^{-4}}{E_{eff/dis}}$ μc/gm tissue to give a dose rate of $\frac{.3}{7}$ rep/day or .3 rep/week.

It is obvious that the value of Q will depend upon the effective energy per disintegration. The attached sheets show the disintegration schemes used and the calculations to obtain Q for the various radioisotopes.

Calculations of the average values for beta emissions are made in the following manner:

E_{av}/emission = bE_{max} where

E_{max} is the maximum energy of the beta emission,

$$b = .33\ (1 - \frac{Z^{\frac{1}{2}}}{43})(1 + \frac{E^{\frac{1}{2}}_{max}}{4})^*,$$ and

Z is the atomic number of the radioelement

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* This is an equation which was suggested by K.Z. Morgan to give approximate values for the average energies of betas which have normal distributions of energies.

In general, $Q = \dfrac{8.2 \times 10^{-4}}{E_{eff}/\text{dis}}$ μc/gm tissue to give a dose rate of .3 rep/week.

E_{eff}/dis is in the dimensions of Mev/dis, and its magnitude will depend upon the contributions made by the average beta and gamma radiation per disintegration.

The gamma ray absorption by the organs is accounted for in the following manner:

$$E_{eff}(\gamma)/\text{emission} = E_{\gamma}\ (1 - e^{-(\mu - \sigma_s)D})$$

where E_{γ} = Mev/photon,

μ = total scattering coefficient for the particular gamma photon and tissue,

σ_s = total scattering coefficient for the particular gamma photon and tissue, and

D = effective thickness of organ in cm.

C. Calculations of Q

The following are calculations which indicate the number of microcuries/gm tissue of the various radioisotopes which are required to give a tissue dose of .3 rep/week. If a different dose rate is required, the proper substitution should be made in equation 7.

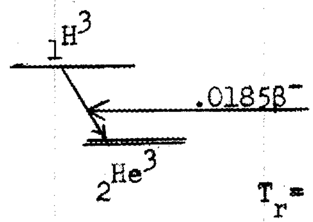
H^3

Using the total body as the principal organ of retention

$b = .33$, $E_m = .0185$ Mev

$E_{eff}/\text{dis} = .33 \times .0185 = .006$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.006} = .137 \ \mu c \ H^3/\text{gm tissue}$$



$T_r = 12.1$ y

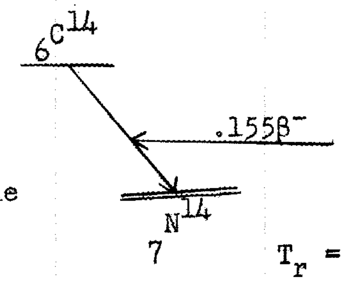
C^{14}

Using adipose tissue as the principal organ of retention

$b = .34$, $E_m = .155$ Mev

$E_{eff}/\text{dis} = .34 \times .155 = .0527$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.0527} = 1.55 \times 10^{-2} \ \mu c \ C^{14}/\text{gm tissue}$$



$T_r = 5100$ y

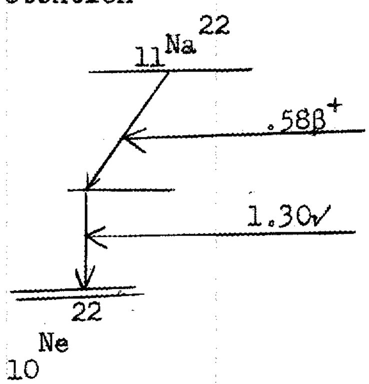
Na^{22}

Using the total body as the principal organ of retention

$b = .362$, $E_m(\beta^+) = .58$ Mev

$E_{av}(\beta^+) = .362 \times .58 = .209$ Mev/dis

$$E_{eff}(\gamma) = E_\gamma \left(1 - e^{-(\mu - \sigma_s)D}\right) \text{ Mev/dis}$$



where $(1 - e^{-(\mu - \sigma_s)D})$ is that fraction of the gamma rays which produce ion pairs,

$T_r = 2.6$ y

$D = 30$ cm (thickness of abdominal region of a 70 Kg man).

$$E_{eff}(\gamma) = 1.3\ (1 - e^{-.028 \times 30}) = .738 \text{ Mev/dis}$$

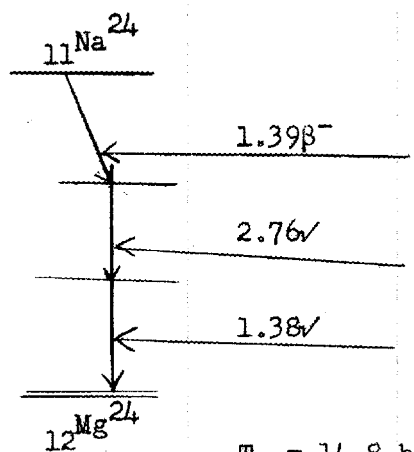
$$E_{eff}/\text{dis} = .209 + .738 = .947 \text{ Mev}$$

$$Q = \frac{8.2 \times 10^{-4}}{.947} = 8.66 \times 10^{-4}\ \mu c\ Na^{22}/\text{gm tissue}$$

Na^{24}

Using the total body as the principal organ of retention

$$b = .39, \quad E_m(\beta^-) = 1.39 \text{ Mev}$$



$T_r = 14.8$ hr.

$$E_{av}(\beta^-) = .39 \times 1.39 = .54 \text{ Mev}$$

Solving for $\Sigma E_{eff}(\gamma)/\text{dis}$, we have

$$\Sigma E_{eff}(\gamma)/\text{dis} = 2.76\ (1 - e^{-.023 \times 30}) +$$

$$+ 1.38\ (1 - e^{-.028 \times 30}) \text{ Mev}$$

$$= 1.373 + .784 = 2.157 \text{ Mev}$$

$$E_{eff}/\text{dis} = .54 + 2.157 = 2.697 \text{ Mev}$$

$$Q = \frac{8.2 \times 10^{-4}}{2.697} = 3.04 \times 10^{-4}\ \mu c\ Na^{24}/\text{gm tissue}$$

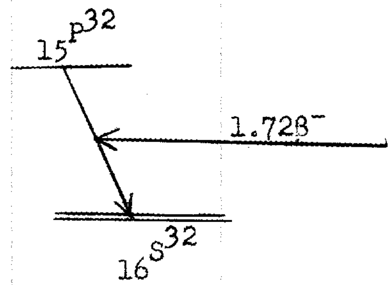
P^{32}

Using bone as the principal organ of retention

$b = .398, \quad E_m = 1.72$ Mev

$E_{eff}/\text{dis} = .398 \times 1.72 = .685$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.685} = 1.2 \times 10^{-3} \ \mu c \ P^{32}/\text{gm tissue}$$



$T_r = 14.3$ d

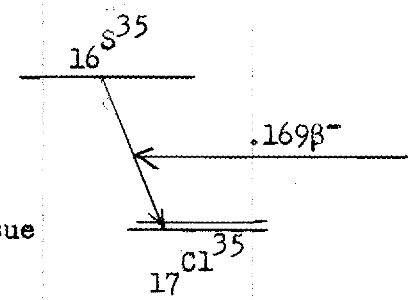
S^{35}

Using skin as the principal organ of retention

$b = .33, \quad E_m = .169$ Mev

$E_{eff}/\text{dis} = .33 \times .169 = .056$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.056} = 1.47 \times 10^{-2} \ \mu c \ S^{35}/\text{gm tissue}$$



$T_r = 87.1$ d

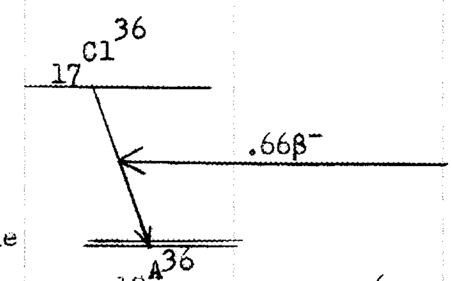
Cl^{36}

Using skin and subcutaneous tissue as the principal organ of retention

$b = .359, \quad E_m = .66$ Mev

$E_{eff}/\text{dis} = .359 \times .66 = .24$ Mev

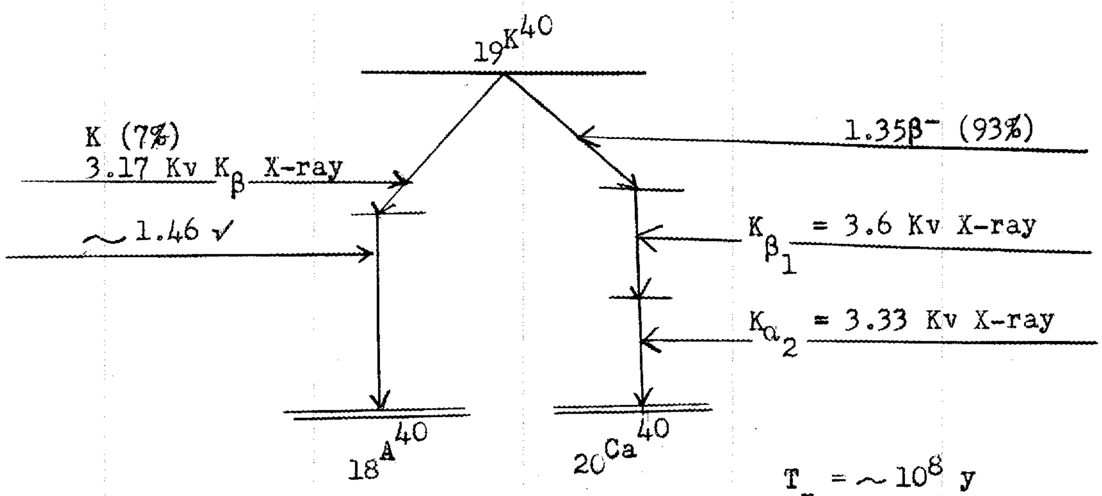
$$Q = \frac{8.2 \times 10^{-4}}{.24} = 3.42 \times 10^{-3} \ \mu c \ Cl^{36}/\text{gm tissue}$$



$T_r = 10^6$ y

<u>K^{40}</u>

Using muscle as the principal organ of retention



$T_r = \sim 10^8$ y

$$E_{eff}/\text{dis} = .93\ (\underset{\beta^-}{bE_m} + \underset{K_{\beta_1}}{E_{eff}} + \underset{K_{\alpha_2}}{E_{eff}}) + .07\ (\underset{K_{\beta_1}}{E_{eff}} + \underset{\checkmark}{E_{eff}})$$

$bE_m\ (\beta^-) = .383 \times 1.35 = .517$ Mev/emission

$E_{eff}\ (K_{\beta_1}) = .0036\ (1 - e^{-100 \times 20}) = .0036$ Mev/emission

$E_{eff}\ (K_{\alpha_2})$ = similar to above = .0033 Mev/emission

$E_{eff}\ (K_{\beta_1})$ = .0032 Mev/emission (K capture X-rays)

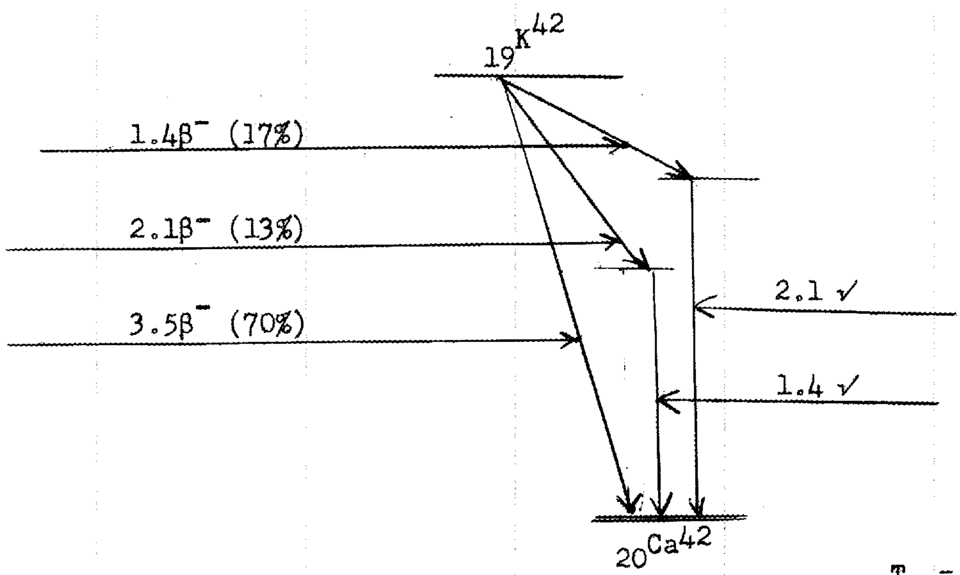
$E_{eff}\ (1.46\checkmark) = 1.46\ (1 - e^{-.0285 \times 20}) = .634$ Mev/emission

$E_{eff}/\text{dis} = .93\ (.517 + .0036 + .0033) + .07\ (.634 + .0032) = .532$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.532} = 1.55 \times 10^{-3}\ \mu c\ K^{40}/\text{gm tissue}$$

K^{42}

Using muscle as the principal organ of retention



T_r = 12.4 hr

$$E_{eff}/\text{dis} = .17 \times b \times \underset{1.4\beta^-}{1.4} + .13 \times b \times \underset{2.1\beta^-}{2.1} + .70 \times b \times \underset{3.5\beta^-}{3.5} + .17 \times \underset{2.1\gamma}{E_{eff}} + .13\ \underset{1.4\gamma}{E_{eff}}$$

$b(1.4\beta^-) = .384$

$b(2.1\beta^-) = .404$

$b(3.5\beta^-) = .435$

$E_{eff}(2.1\gamma)/\text{emission} = 2.1(1 - e^{-.0245 \times 18}) = 2.1 \times .357 = .75$ Mev

$E_{eff}(1.4\gamma)/\text{emission} = 1.4(1 - e^{-.0275 \times 18}) = 1.4 \times .39 = .546$ Mev

$E_{eff}/\text{dis} = .0915 + .1103 + 1.067 + .1275 + .0710 = 1.4673$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{1.4673} = 5.6 \times 10^{-4}\ \mu c\ K^{42}/\text{gm tissue}$$

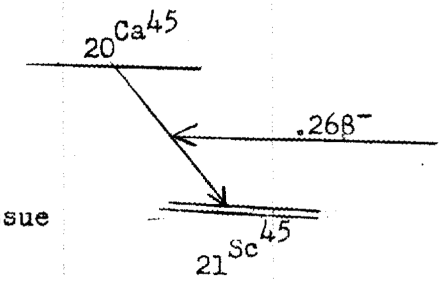
Ca^{45}

Using bone as the principal organ of retention

$b = .33$, $E_m = .26$ Mev

$E_{eff}/\text{dis} = .33 \times .26 = .086$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.086} = .95 \times 10^{-2}\ \mu c\ Ca^{45}/\text{gm tissue}$$



$T_r = 152$ d

Ca^{47}

Using bone as the principal organ of retention

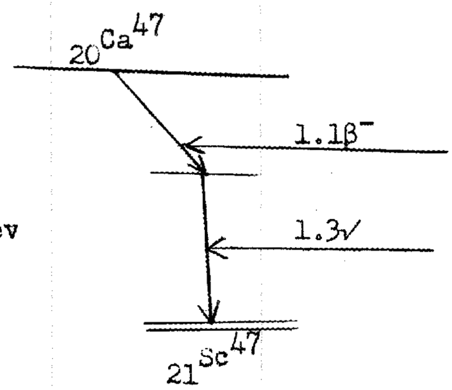
$b = .373$

$E_{eff}(\beta^-)/\text{dis} = .373 \times 1.1 = .410$ Mev

$E_{eff}(\gamma)/\text{dis} = 1.3(1 - e^{-.028 \times 7.6}) = .25$ Mev

$E_{eff}/\text{dis} = .410 + .25 = .66$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.66} = 1.243 \times 10^{-3}\ \mu c\ Ca^{47}/\text{gm tissue}$$



$T_r = 5.8$ d

Ca^{49}

Using bone as the principal organ of retention

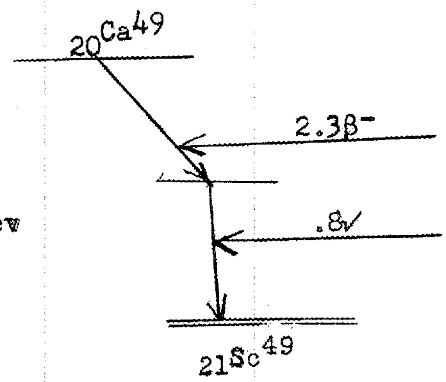
$b = .407$

$E_{eff}(\beta^-)/\text{dis} = .407 \times 2.3 = .936$ Mev

$E_{eff}(\gamma)/\text{dis} = .8(1 - e^{-.0315 \times 7.6}) = .170$ Mev

$E_{eff}/\text{dis} = .936 + .170 = 1.106$ Mev

$Q = \dfrac{8.2 \times 10^{-4}}{1.106} = 7.42 \times 10^{-4}$ µc Ca^{49}/gm tissue



$T_r = 2.5$ hr

Mn^{52}

Using liver as the principal organ of retention

$b = .348$

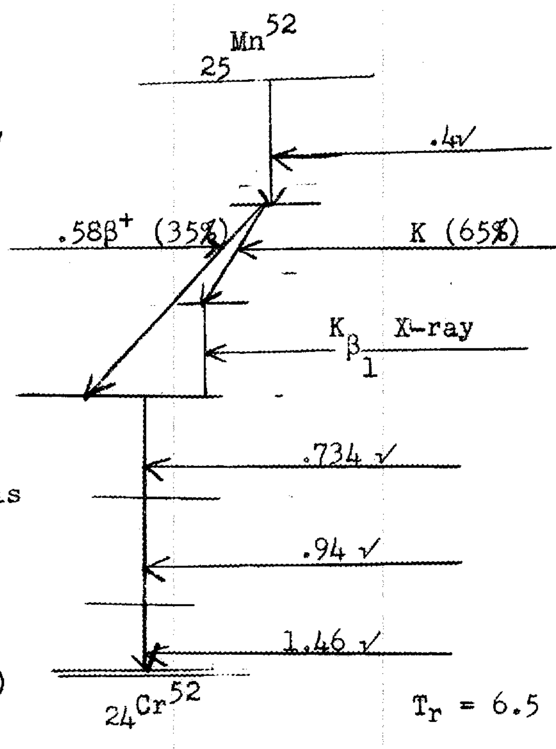
$E_{\beta+}/\text{dis} = .35 \times .348 \times .58 = .071$ Mev

K_{β_1} X-ray $= \dfrac{12407}{2.0806} =$

$= .006$ Mev/emission

(all absorbed)

$= .65 \times .006 = .0039$ Mev/dis



(From 21 min Mn^{52} decay scheme)

$T_r = 6.5$ d

$$E_{eff}(.4\gamma) = .4(1 - e^{-.0315 \times 15}) = .1508 \text{ Mev}$$

$$E_{eff}(.734\gamma) = .734(1 - e^{-.0315 \times 15}) = .2767 \text{ Mev}$$

$$E_{eff}(.94\gamma) = .94(1 - e^{-.0315 \times 15}) = .3544 \text{ Mev}$$

$$E_{eff}(1.46\gamma) = 1.46(1 - e^{-.0195 \times 15}) = .3694 \text{ Mev}$$

$$\sum E_{eff}/\text{dis} = .071 + .0039 + .1508 + .2767 + .3544 + .3694 = 1.226 \text{ Mev}$$

$$Q = \frac{8.2 \times 10^{-4}}{1.226} = 6.68 \times 10^{-4}\ \mu c\ Mn^{52}/\text{gm tissue}$$

<u>Mn^{54}</u>

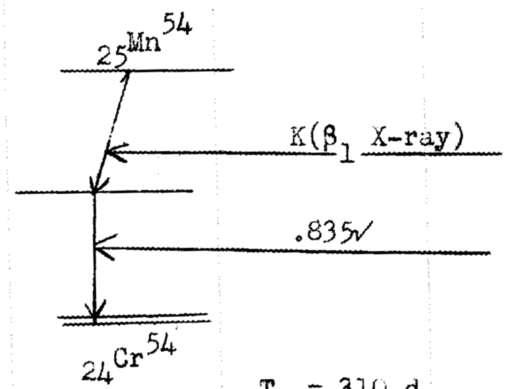
Using liver as the principal organ of retention

$$E(K_{\beta_1}\ \text{X-ray})/\text{dis} = .006 \text{ Mev (See } Mn^{52})$$

$$E_{eff}(\gamma) = .835\ (1 - e^{-.031 \times 15}) = .361 \text{ Mev}$$

$$E_{eff}/\text{dis} = .006 + .361 = .367 \text{ Mev}$$

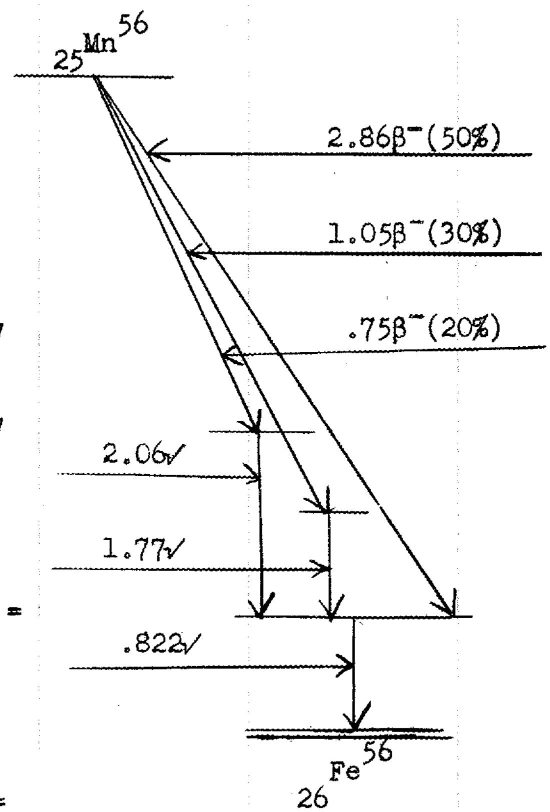
$$Q = \frac{8.2 \times 10^{-4}}{.367} = 2.24 \times 10^{-3}\ \mu c\ Mn^{54}/\text{gm tissue}$$



$T_r = 310$ d

Mn^{56}

Using liver as the principal organ of retention



$T_r = 2.59$ hr.

$b\ (2.86\beta^-) = .415$

$b\ (1.05\beta^-) = .366$

$b\ (.75\beta^-) = .355$

$E_{eff}(2.86\beta^-)/\text{dis} = .5 \times .415 \times 2.86 = .594$ Mev

$E_{eff}(1.05\beta^-)/\text{dis} = .3 \times .366 \times 1.05 = .115$ Mev

$E_{eff}(.75\beta^-)/\text{dis} = .2 \times .355 \times .75 = .053$ Mev

$E_{eff}(2.06\gamma)/\text{dis} = .2 \times 2.06(1 - e^{-.0245 \times 15}) =$

$= .127$ Mev

$E_{eff}(1.77\gamma)/\text{dis} = .3 \times 1.77(1 - e^{-.026 \times 15}) =$

$= .172$ Mev

$E_{eff}(.822\gamma)/\text{dis} = 1 \times .822(1 - e^{-.032 \times 15}) =$

$= .313$ Mev

$\sum E_{eff} = .594 + .115 + .053 + .127 + .172 + .313 = 1.374$ Mev/dis

$Q = \dfrac{8.2 \times 10^{-4}}{1.374} = 5.96 \times 10^{-4}\ \mu c\ Mn^{56}/\text{gm tissue}$

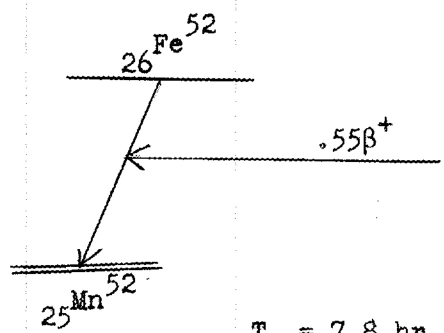
Fe^{52}

Using blood as the principal organ of retention

$b = .345$

$E_{eff} = .345 \times .55 = .190$ Mev

$$Q = \frac{8.4 \times 10^{-4}}{.19} = 4.3 \times 10^{-3} \ \mu c \ Fe^{52}/gm \text{ tissue}$$

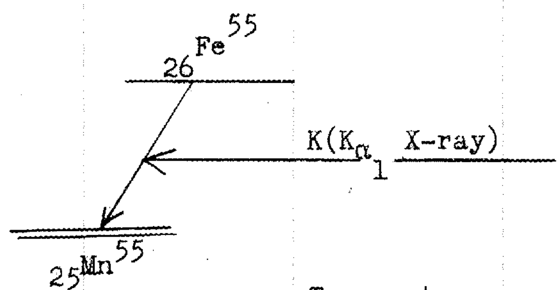


$T_r = 7.8$ hr.

Fe^{55}

Using blood as the principal organ of retention

According to Seaborg and Perlman (Rev. M.P., Vol. 20, October 1948) Fe^{55} decays by K capture. There are no internal conversion electrons,



$T_r = \sim 4$ yr.

positrons, nor gammas. Fe^{55} would therefore decay to Mn^{55}. According to Peacock, et al, (J. Clin. Invest., Vol. XXV, July 1946), the most abundant and most energetic x-rays has emitted an energy equivalent to the K_{α_1} line of Mn^{55}. Therefore,

$E_{eff} = \frac{12407}{2.0975} = 5.1915$ Kv, energy of the K_{α_1} line of Mn^{55} which is monoenergetic.

$$Q = \frac{8.2 \times 10^{-4}}{5.915 \times 10^{-3}} = .139\ \mu c\ Fe^{55}/gm \text{ tissue}$$

$\underline{Fe^{59}}$

Using the liver* as the principal organ of retention

$b(.26\beta^-) = .33$

$b(.46\beta^-) = .49$

$E_{eff}(.26\beta^-)/dis = .5 \times .33 \times .26 = .043$ Mev

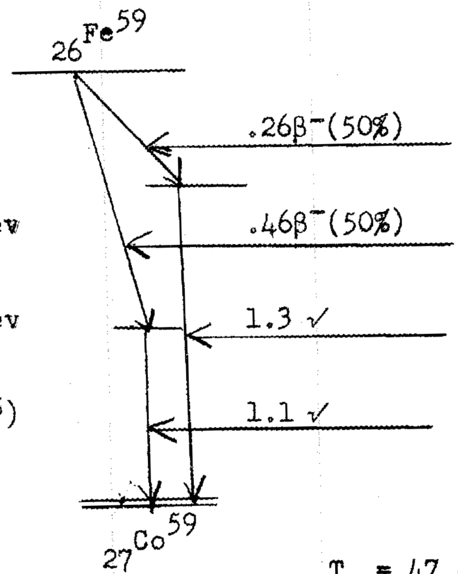
$E_{eff}(.46\beta^-)/dis = .5 \times .49 \times .46 = .113$ Mev

$E_{eff}(1.3\gamma)/dis = .5 \times 1.3\ (1 - e^{-.028 \times 15})$

$= .223$ Mev

$E_{eff}(1.1\gamma)/dis = .5 \times 1.1(1 - e^{-.029 \times 15})$

$= .196$ Mev



$T_r = 47$ d

$\sum E_{eff}/dis = .043 + .113 + .223 + .191 = .575$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.575} = 1.427 \times 10^{-3}\ \mu c\ Fe^{59}/gm \text{ tissue}$$

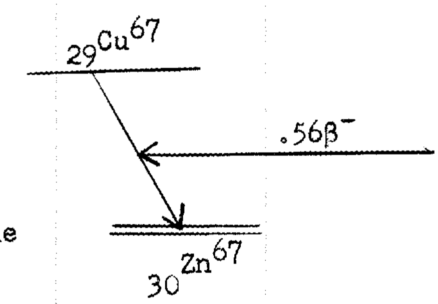
---

* The liver has been selected as the principal organ of retention in order to account for the gamma absorption. It will be noted that the iron concentration in the liver is the same as that in the blood.

Cu^{67}

Using the liver as the principal organ of retention

b = .342



E_{eff} = .342 x .56 = .191 Mev

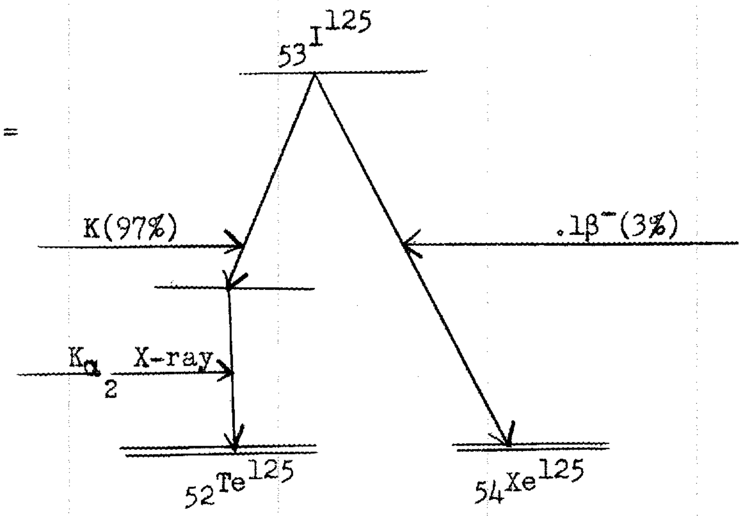
$Q = \frac{8.2 \times 10^{-4}}{.191} = 4.3 \times 10^{-3}$ μc Cu^{67}/gm tissue

T_r = 56 hr.

I^{125}

Using the thyroid as the principal organ of retention

b = .296



$E_{eff}(\beta^-)$/dis = .03 x .1 x .296 =

= .0008 Mev

$E(K_{\alpha_2}\text{ X-ray}) = \frac{12407}{.45045}$

= .0276 Mev

T_r = 56 d

$E_{eff}(K_{\alpha_2}\text{ X-ray}) = .97 \times .0276(1 - e^{-.2 \times 3}) = .0122$ Mev

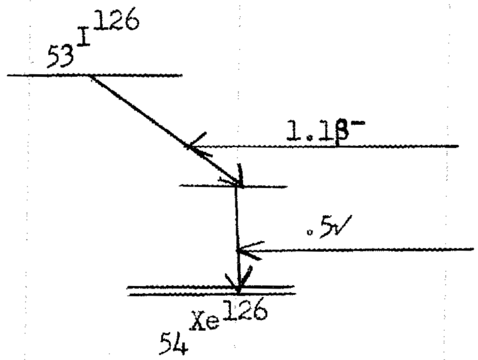
E_{eff}/dis = .0008 + .0122 = .013 Mev

$Q = \frac{8.2 \times 10^{-4}}{.013} = 6.3 \times 10^{-2}$ μc I^{125}/gm tissue

I^{126}

Using the thyroid as the principal organ of retention

$b = .346$



$E_{eff}(\beta^-) = .346 \times 1.1 = .381$ Mev

$E_{eff}(\gamma) = .5(1 - e^{-.032 \times 3}) = .0455$ Mev

$E_{eff}/\text{dis} = .381 + .0455 = .4265$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.4265} = 1.92 \times 10^{-3}\ \mu c\ I^{126}/\text{gm tissue}$$

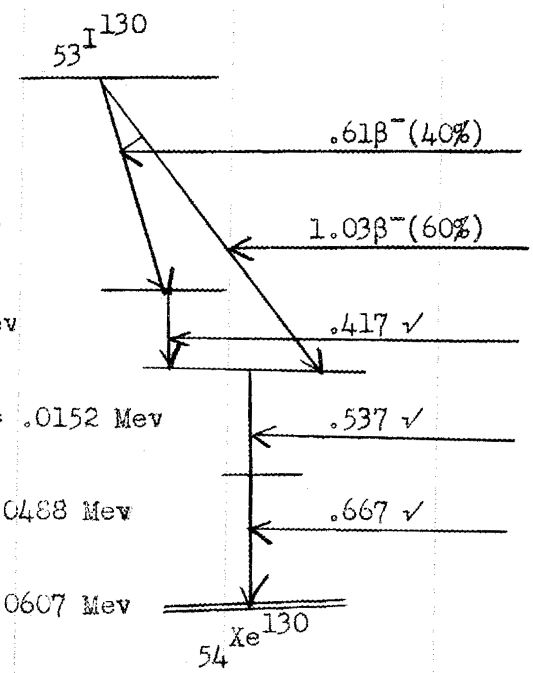
$T_r = 13$ d

I^{130}

Using the thyroid as the principal organ of retention

$b(.61\beta^-) = .327$

$b(1.03\beta^-) = .343$



$E_{eff}(.61\beta^-)/\text{dis} = .40 \times .327 \times .61 = .0798$ Mev

$E_{eff}(1.03\beta^-)/\text{dis} = .60 \times .343 \times 1.03 = .212$ Mev

$E_{eff}(.417\gamma)/\text{dis} = .40 \times .417(1 - e^{-.032 \times 3}) = .0152$ Mev

$E_{eff}(.537\gamma)/\text{dis} = 1 \times .537(1 - e^{-.032 \times 3}) = .0488$ Mev

$E_{eff}(.667\gamma)/\text{dis} = 1 \times .667(1 - e^{-.032 \times 3}) = .0607$ Mev

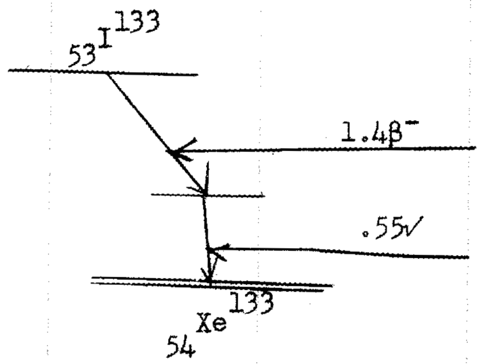
$T_r = 12.6$ hr.

$\sum E_{eff}/\text{dis} = .0798 + .212 + .0152 + .0488 + .0607 = .4165$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.4165} = 1.97 \times 10^{-3}\ \mu c\ I^{130}/\text{gm tissue}$$

I^{133}

Using the thyroid as the principal organ of retention



$b = .355$

$E_{eff}(\beta^-)/\text{dis} = .355 \times 1.4 = .497$ Mev

$E_{eff}(\gamma)/\text{dis} = .55(1 - e^{-.032 \times 3}) = .050$ Mev

$E_{eff}/\text{dis} = .497 + .050 = .547$ Mev

$$Q = \frac{8.2 \times 10^{-4}}{.547} = 1.5 \times 10^{-3}\ \mu c\ I^{133}/\text{gm tissue}$$

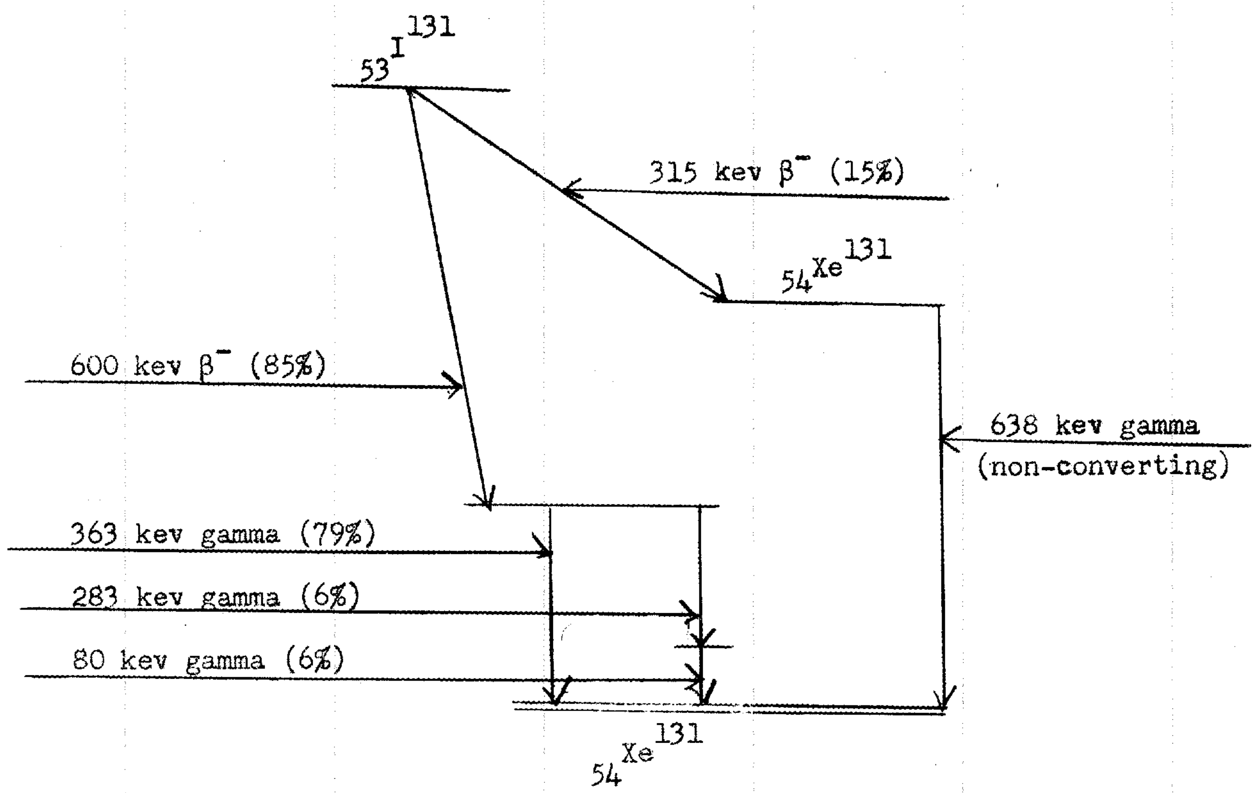
$T_r = 22$ hr

Internal Dose Determinations

I^{131}

Using the thyroid as the principal organ of retention

For the purpose of calculating Q for I^{131}, I have chosen the decay scheme which was suggested by Metzger and Deutsch(1).



$T_r = 8$ d

Table I

Energy in kev	Intensity rays/100 disintegration	Conversion Coefficient Ne/Nγ	N_K/N_L
80 ± 1	6	0.8 ± 0.5	5.5 ± 2.5
283 ± 3	6	0.05 ± 0.02	> 2
363 ± 3	79	0.019 ± 0.005	5.2 ± 1.5
638 ± 5	15	< .005	---

(1) F. Metzger and M. Deutsch, THE PHYSICAL REVIEW, V. 74, 2nd Series, No. 11, 12-1-48.

For the .638 Mev non-converting gamma ray

$$E_{eff}/\text{dis} = .15 \times .638(1 - e^{-.032 \times 3}) = 8.7 \text{ kev}$$

For the converting gamma rays (Gammas competing with electrons, and conserving energy)

$$E_{eff}(.363\gamma)/\text{dis} = .79 \times .363(1 - e^{-.0315 \times 3}) \times \frac{1}{1.019} = 25.4 \text{ kev}$$

$$E_{eff}(.283\gamma)/\text{dis} = .06 \times .283(1 - e^{-.0308 \times 3}) \times \frac{1}{1.05} = 1.42 \text{ kev}$$

$$E_{eff}(.080\gamma)/\text{dis} = .06 \times .080(1 - e^{-.0268 \times 3}) \times \frac{1}{1.8} = .2 \text{ kev}$$

$$E_{eff}(\text{converting } \gamma\text{s}) = .02702 \text{ Mev}$$

For the X-rays, we shall use the K_{β_2} and L_{β_2} energies as approximating the energies/emission.

$$\frac{\text{Iodine } K_{\beta_2} - \text{Caesium } K_{\beta_2}}{2} = \frac{.37466 - .34512}{2} = .01475 \text{ Å difference}$$

between iodine and xenon.

$$\text{Xenon } K_{\beta_2} = .37466 - .01475 = .35991 \text{ Å}$$

$$E(\text{Xe } K_{\beta_2})/\text{emission} = \frac{12407}{.35991} = 34.5 \text{ kv energy}$$

Therefore, the K_{β_2} emissions for the .363, .283, and the .080 Mev conversion process will each have energies of .0345 Mev.

Similarly for the L_{β_2} emissions, we have

$$\frac{\text{Iodine } L_{\beta_2} - \text{Caesium } L_{\beta_2}}{2} = \frac{2.7461 - 2.5064}{2} = .1199 \text{ Å difference}$$

$$\text{Xenon } L_{\beta_2} = 2.7461 - .1199 = 2.6262 \text{ Å}$$

$$E(\text{Xe } L_{\beta_2})/\text{emission} = \frac{12407}{2.6262} = 4.73 \text{ kv energy}$$

Therefore the L_{β_2} emissions for the .363, .283, and the .080 Mev conversion process will each have energies of .00473 Mev.

Calculating the energies/disintegration of the X-rays which are associated with the various conversion processes, we have:

$$E_{eff}(.363\ K_{\beta_2})/\text{dis} = .0345(1 - e^{-.1075 \times 3})(.79 \times \frac{.019}{1.019} \times \frac{5.2}{6.2}) = .0001 \text{ Mev}$$

$$E_{eff}(.363\ L_{\beta_2})/\text{dis} = .0047(1 - e^{-46 \times 3})(.79 \times \frac{.019}{1.019} \times \frac{1}{6.2}) = .00001 \text{ Mev}$$

$$E_{eff}(.283\ K_{\beta_2})/\text{dis} = .0345(1 - e^{-.1075 \times 3})(.06 \times \frac{.05}{1.05} \times \frac{2}{3}) = .00002 \text{ Mev}$$

$$E_{eff}(.283\ L_{\beta_2})/\text{dis} = .0047(1 - e^{-46 \times 3})(.06 \times \frac{.05}{1.05} \times \frac{1}{3}) = .000005 \text{ Mev}$$

$$E_{eff}(.080\ K_{\beta_2})/\text{dis} = .0345(1 - e^{-.1075 \times 3})(.06 \times \frac{.8}{1.8} \times \frac{5.5}{6.5}) = .0002 \text{ Mev}$$

$$E_{eff}(.080\ L_{\beta_2})/\text{dis} = .0047(1 - e^{-46 \times 3})(.06 \times \frac{.8}{1.8} \times \frac{1}{6.5}) = .00002 \text{ Mev}$$

$\sum E_{eff}$/dis of the conversion process X-rays = .000355 Mev

The energy of an internal conversion electron is the difference between the available energy for the converting process minus the binding energy of the orbit under consideration. The available conversion energies are .080, .283, and .363 Mev. The binding energies are about .0345 and .0047 Mev for the K and L shells of Xenon respectively.

Calculating the energies/disintegration of the conversion electrons which are associated with the various conversion energies, we have:

$$E_{eff}(.363e^-_K)/dis = (.363 - .0345)(.79 \times \frac{.019}{1.019} \times \frac{5.2}{6.2}) = .00406 \text{ Mev}$$

$$E_{eff}(.363e^-_L)/dis = (.363 - .0047)(.79 \times \frac{.019}{1.019} \times \frac{1}{6.2}) = .00085 \text{ Mev}$$

$$E_{eff}(.283e^-_K)/dis = (.283 - .0345)(.06 \times \frac{.05}{1.05} \times \frac{2}{3}) = .00047 \text{ Mev}$$

$$E_{eff}(.283e^-_L)/dis = (.283 - .0047)(.06 \times \frac{.05}{1.05} \times \frac{1}{3}) = .000264 \text{ Mev}$$

$$E_{eff}(.080e^-_K)/dis = (.080 - .0345)(.06 \times \frac{.8}{1.8} \times \frac{5.5}{6.5}) = .001027 \text{ Mev}$$

$$E_{eff}(.080e^-_L)/dis = (.080 - .0047)(.06 \times \frac{.8}{1.8} \times \frac{1}{6.5}) = .00031 \text{ Mev}$$

$\sum E_{eff}$/dis for the conversion electrons = .00698 Mev

The effective energies/disintegration of the betas are:

$b(.6\beta^-) = .326$

$E_{eff}(.6\beta^-) = .326 \times .6 \times .85 = .166$ Mev/dis

$b(.315\beta^-) = .312$

$E_{eff}(.315\ \beta^-) = .312 \times .315 \times .15 = .015$ Mev/dis

$\sum E_{eff}(\beta^- s)$/dis $= .181$ Mev

$$\sum E_{eff}/\mathrm{dis} = E_{eff}/\mathrm{dis}(\text{non-converting } \gamma) + E_{eff}/\mathrm{dis}(\text{converting } \gamma) +$$

$$+ E_{eff}/\mathrm{dis}(\text{X-rays}) + E_{eff}/\mathrm{dis}(\text{converting } e^{-}\text{s}) + E_{eff}/\mathrm{dis}(\beta^{-})$$

$$= .0087 + .02702 + .00036 + .00698 + .181$$

$$= .22406 \simeq .224 \text{ Mev}$$

$$Q = \frac{8.2 \times 10^{-4}}{.224} = 3.66 \times 10^{-3} \ \mu c \ I^{131}/\text{gm tissue}$$

Table II

Tabulation of Calculations for I^{131} Using the Thyroid as the Principal Organ of Retention

(1) Type Radiation	(2) Energy (max) in kev per emission	(3) b	(4) b x E_{max} (E_{av}) kev	(5) Number per 100 disintegrations	(6) $1 - e^{-(\mu-\sigma_s)D}$ (fraction)	(7) Energy absorbed in 3 cm dia. sphere of tissue/dis kev
β^-	600	.326	196	85		
β^-	315	.312	98	15		
γ	638			15	.091	8.7
γ	363			77.527	.09	25.4
e^-_K	328.5	1	328.5	1.237		
e^-_L	358.3	1	358.3	.238		
X_K	34.5			1.237	.276	0.1
X_L	4.7			.238	1	.01
γ	283			5.7142	.088	1.42
e^-_K	248.5	1	248.5	.1905		
e^-_L	278.3	1	278.3	.0952		
X_K	34.5			.1905	.276	0.02
X_L	4.7			.0952	1	.005
γ	80			3.34	.077	0.2
e^-_K	45.5	1	45.5	2.25		
e^-_L	75.3	1	75.3	.41		
X_K	34.5			2.25	.276	.2
X_L	4.7			.41	1	.02

Table II
(Continued)

(1) Type Radiation	(2) Energy (max) in kev per emission	(8) Energy Absorbed per Disintegration kev	(9) Contributions to the total effective Mev/disintegration Per cent	(10) Half-thickness in tissue cm	(11) Range in tissue cm
β^-	600	166	74.1		0.2
β^-	315	15	6.7		0.08
γ	638		3.87	8.2	
γ	363		11.33	6.4	
e^-_K	328.5	4.06	1.815		0.09
e^-_L	358.3	.85	.379		0.11
X_K	34.5		.04	2.4	
X_L	4.7		.004	0.02	
γ	283		.63	5.8	
e^-_K	248.5	0.47	.209		0.06
e^-_L	278.3	0.26	.116		0.07
X_K	34.5		.08	2.4	
X_L	4.7		.002	0.02	
γ	80		.09	4	
e^-_K	45.5	1.03	.460		0.01
e^-_L	75.3	.31	.138		0.01
X_K	34.5		.08	2.4	
X_L	4.7		.008	0.02	
Betas		181.0	80.78		
Gammas		35.72	15.94		
e^-s		6.98	3.12		
X-rays		.36	.16		

Note: (1) Range = .407 x $E^{1.38}$ gm/cm^2 $\cong$ cm of tissue. Ranges are for the betas and internal conversion electrons.

(2) Binding energies for the K and L shells of Xenon are estimated as being midway between similar energies of iodine and cesium. In each case, the K_{β_2} and L_{β_2} energies were used.

The decay scheme for I^{131} and Tables I and II give a good picture of the contributions made by the various betas, gammas, conversion electrons (e^-), and x-rays per disintegration. The attached work sheets show all calculations and assumptions.

It will be noted that the betas and gammas contribute about 81 and 16 per cent respectively to the total effective energy which is absorbed by the thyroid tissue. The e^- and the x-rays contribute about 3 and 0.2 per cent respectively. It appears that the contribution by the x-rays could be ignored when calculating Q, without changing the value too much.

The selection of an equivalent body having a thickness of 3 cm, to represent the equivalent thyroid in the determination of the energy absorbed by the gammas and x-rays, was made after some discussion. Most references list the thyroid weight as about 30 gm. "Gray's Anatomy" lists the dimensions of such a thyroid as about 3 x 2 x 5 cm for each lobe. According to "Mayo's", the weight of a normal thyroid gland is approximately 15 grams. It is obvious that the above dimensions (3 x 2 x 5 cm) should probably be somewhat smaller. The figure of 3 cm represents the thickness of one equivalent body which is substituted for the bi-lobed thyroid gland. We believe that the figure is on the "large" side; however, it is in the safe direction since the contribution by the gammas to the total dose (16%) would be smaller if a thickness of smaller value were used. This would reduce the x-ray contribution also.

D. Details of Calculation of Daily Element Intake and of Permissible Concentrations

Calculation of Hydrogen Intake per Day

3000 Calorie intake/day (Assumption)

130.4 gm Protein	(7% H)	=	9.13 gm H
130.4 gm Fat	(~12.4% H)	=	16.2 gm H
326 gm Carbohydrate	(~6.5% H)	=	21.2 gm H
Total H from food			46.53 gm H

From water, we have

$$2H + O \longrightarrow H_2O$$

2	18
x	2200

$$x = \frac{2 \times 2200}{18} = 244 \text{ gm H}$$

Total H becomes

via food 46.53 gm

via water 244 gm

I = total H intake per day

Calculation of Carbon Intake per Day

3000 Calorie intake per day (assumption)

130.4 gm Protein has	56 gm	carbon physiologically available
130.4 gm Fat has	103 gm	carbon physiologically available
326 gm Carbohydrate has	121 gm	carbon physiologically available
	280 gm	carbon total above

Calculation of f_2 for adipose tissue

Triglycerides

	gm M	C^{14}	Fraction C^{12}
7% Stearic Acid C_{18} H_{36} O_2	284.47	216	.76
45% Oleic Acid C_{18} H_{34} O_2	282.46	216	.77
10% Linoleic Acid C_{18} H_{32} O_2	280.44	216	.77
25% Palmitic Acid C_{16} H_{32} O_2	256.42	192	.75
4% Myristic Acid C_{14} H_{28} O_2	228.37	168	.74
6% Palmitoleic Acid C_{16} H_{28} O_2	252.39	192	.76
Trace arachidonic acid C_{20} H_{40} O_2	312.52	240	.77
Trace tetradecenoic acid C_{14} H_{28} O_2	194.35	168	.86
			$\sim$ 76-1/2%

98% of the triglycerides of human fat tissue is $\sim$76-1/2% carbon by weight

75-95% (av 85%) of adipose depot tissue (fat) is triglycerides

Therefore .85 x .98 x .765 = $\sim$64% of adipose tissue is carbon.

$$f_2 = \frac{\text{carbon in adipose tissue}}{\text{carbon in body}} = \frac{12.6\ \text{Kg fat} \times .64}{12.6\ \text{Kg carbon in body}} = .64$$

Selection of Phosphorus and Calcium Content of Bone and Phosphorus Intake per Day

Inasmuch as elemental phosphorus is required by the body each day in minimal amounts and that most of the phosphorus is deposited in the skeleton, calculations were based upon the following assumptions:

1. The average minimum requirement of phosphorus for normal adult persons is about 1.2 gm per day. This figure is based upon the average of minimum amounts from six sources. The amounts vary from 0.88 to 1.82 gm/day. An alternative would be to use 1.58 gm/day which Sherman[(2)] found to be the average of 150 American dietaries, the phosphorus content of which varied from 0.60 to 2.79 gm/day.

2. On the basis of a 7000 gm skeleton, excluding bone marrow, 550 gm for the phosphorus content of bone was selected. This figure was calculated from the averages of 6 references for phorphorus, varying between 490 and 570 gm, and 10 references for calcium, varying between 1050 and 1616 gm. Adjustments of both averages (about 5.5%) were made in order to conform to the Ca/P ratio of 2.2. This latter ratio appears to be the acceptable ratio, although 2.15 is the calculated ratio for the apatite molecule $CaCO_3 \cdot 3Ca_3(PO_4)_2$.

(2) Sherman, H.C., CHEMISTRY OF FOOD AND NUTRITION, The MacMillan Company

$$\frac{10(\text{atoms Ca}) \times 40(\text{atomic wt. Ca})}{6(\text{atoms P}) \times 31(\text{atomic wt. P})} = \frac{400}{186} = 2.15$$

The 2.2 value can be justified as follows:

Choosing 3233 gm as ash content of 7000 gm skeleton, for the Ca_3PO_4 portion of the apatite molecule, we have:

$$3233 \text{ gm (ash)} \times .8(Ca_3PO_4) \times .3876 \text{ (Ca)} \cong 1002 \text{ gm Ca}$$

$$3233 \text{ gm} \times .8 \times .1997 \text{ (P)} \cong 516 \text{ gm P}$$

For the $CaCO_3$ portion, we have:

$$3233 \text{ gm (ash)} \times .13 \ (CaCO_3) \times .4 \text{ (Ca)} \cong 168 \text{ gm Ca}$$

For the $Mg_3(PO_4)_2$ portion, we have:

$$3233 \text{ gm (ash)} \times .02 \ (Mg_3(PO_4)_2) \times .2775 \text{ (Mg)} \cong 18 \text{ gm Mg}$$

$$3233 \text{ gm} \times .02 \times .2357 \text{ (Ca)} \cong 15.2 \text{ gm P}$$

Our Ca/P ratio becomes

$$\frac{1002 + 168}{516 + 15.2} = \frac{1170}{531.2} \cong \underline{\underline{2.2}}$$

Note that this calculation is based upon an average of three references for "ash", and upon one reference for the other fractions. The calculated ratio will vary, according to the particular reference used in the calculations.

Selection of Iodine Intake per day

Inasmuch as normal persons must have a minimum iodine intake which will maintain a certain body, and thyroid, iodine content, we may calculate the P.D. on the basis of an equilibrium state.

The average of sixteen references shows that the minimum intake per day for normal people is 56 μgm. These references vary between 14 and 150 μgm per day.

This figure (56 μgm) may be checked by considering[2] that about 300 μgm of thyroxine (equivalent to 200 μgm iodine) is catabolized each day. About four-fifths of the iodine thus catabolized is used over again, leaving about one-fifth to be made up by daily intake. 1/5 x 200 μgm I = 40 μgm I daily make-up, which is in close agreement with 56 μgm daily intake.

Selection of Iodine Content of the Thyroid

For the iodine content of the thyroid gland three particular references were chosen to obtain an average value for the P.D. calculation.

1. 35 mg per 100 gm thyroid tissue (35 mg%), which gives 7 mg I per 20 gm thyroid. This reference does not state the number of thyroids used to make this determination; however, the statement is clear concerning the ratio of iodine to grams of tissue.

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(2) MINERAL METABOLISM by Shohl, 1939 edition
MEDICAL BIOCHEMISTRY by Everett, 2nd edition

2. 8.8 mg I per thyroid. This is an average of 150 determinations on persons who had lived in Charleston, South Carolina. We do not know the terminal states of the thyroids in these cases.

3. 10 mg I per thyroid. This is the usual statement of iodine content of the thyroid gland. The thyroid weight is usually not mentioned. When it is mentioned, values of about 30 gm are given.

An average of these three values, based upon a 20 gm normal thyroid is about 8 mg I per 20 gm thyroid. This figure will be used in the P.D. determination.

Daily intakes and organ contents of the other elements are readily obtainable from the literature. The values listed in the tables are averaged values which were obtained from several sources.

Table III

Tabulation of the Calculations of the Radioisotopes of the Elements Which Are Common to the Body Metabolism

	Radio Element (1)	Kind of Radiation (2)	Eff. E Per Dis. Mev E_{eff} (3)	Selected Critical Organ (SCO) Name (4)	Weight gms. m (5)	Con. of element in SCO (av) gms element per gm organ c (6)	Daily Intake Element gms. I (7)
1	H^3	β^-	.006	Body	70,000	0.1	291
2	C^{14}	β^-	.053	Adipose	12,600	0.64	280
3	Na^{22}	β^+, γ	.947	Body	70,000	9.7×10^{-4}	4
4	Na^{24}	β^-, γ	2.697	Body	70,000	9.7×10^{-4}	4
5	P^{32}	β^-	.685	Bone	7,000	7.86×10^{-2}	1.2
6	S^{35}	β^-	.056	Skin	4.8×10^{-3}	3.75×10^{-3}	1.3
7	Cl^{36}	β^-	.240	Skin and Subcutaneous	8,500	3×10^{-3}	7.8
8	K^{40}	β^-,γ,K	.531	Muscle	30,000	3×10^{-3}	3.3
9	K^{42}	β^-, γ	1.467+	Muscle	30,000	3×10^{-3}	3.3
10	Ca^{45}	β^-	.086	Bone	7,000	0.173	0.9
11	Ca^{47}	β^-, γ	.66	Bone	7,000	0.173	0.9
12	Ca^{49}	β^-, γ	1.106	Bone	7,000	0.173	0.9
13	Mn^{52}	β^+,γ,K	1.226	Liver	1,700	1.7×10^{-6}	3×10^{-3}
14	Mn^{54}	K, γ	.367	Liver	1,700	1.7×10^{-6}	3×10^{-3}
15	Mn^{56}	β^-, γ	1.374	Liver	1,700	1.7×10^{-6}	3×10^{-3}
16	Fe^{52}	β^+	.19	Blood	5,000	5×10^{-4}	12×10^{-3}
17	Fe^{55}	K only	.006	Blood	5,000	5×10^{-4}	12×10^{-3}
18	Fe^{59}	β^-, γ	.575	Liver	1,700	5×10^{-4}	12×10^{-3}
19	Cu^{67}	β^-	.191	Liver	1,700	$.9 \times 10^{-5}$	1.75×10^{-3}
20	I^{125}	K, β^-	.013	Thyroid	20	4×10^{-4}	56×10^{-6}
21	I^{126}	β^-, γ	.1265	Thyroid	20	4×10^{-4}	56×10^{-6}
22	I^{130}	β^-, γ	.4165	Thyroid	20	4×10^{-4}	56×10^{-6}
23	I^{131}	β^-, γ	.224	Thyroid	20	4×10^{-4}	56×10^{-6}
24	I^{133}	e^-, x β^-, γ	.547	Thyroid	20	4×10^{-4}	56×10^{-6}

Table III (Continued)

Fraction of element which enters blood via Lungs or G-I Tract (f_1); which enters organ from blood (f_2).

$$f_1 \times f_2 = f_L \text{ or } f_G$$

	VIA LUNGS			VIA G-I TRACT		
	f_1 (8)	f_2 (9)	f_L (10)	f_1 (11)	f_2 (12)	f_G (13)
1	.75	1	.75	1	1	1
2	.75	.64	.48	1	.64	.64
3	.75	1	.75	1	1	1
4	.75	1	.75	1	1	1
5	.75	.786	.59	1	.786	.786
6	.75	.17	.128	1	.17	.17
7	.75	.243	.18	1	.243	.243
8	.75	.465	.35	1	.465	.465
9	.75	.465	.35	1	.465	.465
10	.75	.99	.74	1	.99	.99
11	.75	.99	.74	1	.99	.99
12	.75	.99	.74	1	.99	.99
13	.75	.0145	.011	1	.0145	.0145
14	.75	.0145	.011	1	.0145	.0145
15	.75	.0145	.011	1	.0145	.0145
16	.75	.556	.416	1	.556	.556
17	.75	.556	.416	1	.556	.556
18	.75	.189	.142	1	.189	.189
19	.75	.153	.11	1	.153	.153
20	.75	.27	.20	1	.27	.27
21	.75	.27	.20	1	.27	.27
22	.75	.27	.20	1	.27	.27
23	.75	.27	.20	1	.27	.27
24	.75	.27	.20	1	.27	.27

Table III (Continued)

	Half-Lives for Element in SCO			Decay Constants for Element in SCO		
	Biological	Radiological	Effective	Biological	Radiological	Effective
	$\frac{.693}{\lambda_b} = T_b$ days (14)	T_r days (15)	$\frac{.693}{\lambda} = T$ days (16)	$\frac{If_G}{mc} = \lambda_b$ days^{-1} (17)	$\frac{.693}{T_r} = \lambda_r$ days^{-1} (18)	$\lambda_b + \lambda_r = \lambda$ days^{-1} (19)
1	16.7	4.416×10^3	16.6	4.16×10^{-2}	1.57×10^{-4}	4.18×10^{-2}
2	31.2	1.86×10^6	31.2	2.22×10^{-2}	0	2.22×10^{-2}
3	11.8	949	11.6	5.88×10^{-2}	7.33×10^{-4}	5.95×10^{-2}
4	11.8	.617	.587	5.88×10^{-2}	1.12	1.18
5	405	14.3	13.8	1.71×10^{-3}	4.85×10^{-2}	5.02×10^{-2}
6	56.3	87.1	34.1	1.23×10^{-2}	7.96×10^{-3}	2.03×10^{-2}
7	9.32	7.3×10^8	9.32	7.44×10^{-2}	0	7.44×10^{-2}
8	40.7	6.57×10^{11}	40.7	1.7×10^{-2}	0	1.7×10^{-2}
9	40.7	.517	.51	1.7×10^{-2}	1.34	1.36
10	942	152	131	7.36×10^{-4}	4.56×10^{-3}	5.3×10^{-3}
11	942	5.8	5.77	7.36×10^{-4}	.119	.12
12	942	.104	.104	7.36×10^{-4}	6.66	6.66
13	46.2	6.5	5.68	1.5×10^{-2}	.107	.122
14	46.2	310	40.3	1.5×10^{-2}	2.24×10^{-3}	1.72×10^{-2}
15	46.2	.108	.108	1.5×10^{-2}	6.42	6.44
16	259	.325	.325	2.67×10^{-3}	2.13	2.13
17	259	1.46×10^3	220	2.67×10^{-3}	4.75×10^{-4}	3.15×10^{-3}
18	259	46.3	39.1	2.67×10^{-3}	1.5×10^{-2}	1.77×10^{-2}
19	39.6	2.33	2.16	1.75×10^{-2}	.298	.32
20	366	56	48.5	1.89×10^{-3}	1.24×10^{-2}	1.43×10^{-2}
21	366	13	12.5	1.89×10^{-3}	5.33×10^{-2}	5.52×10^{-2}
22	366	.525	.525	1.89×10^{-3}	1.32	1.32
23	366	8	7.83	1.89×10^{-3}	8.67×10^{-2}	8.86×10^{-2}
24	366	.917	.914	1.89×10^{-3}	.756	.758

Table III (Continued)

	μc/gm SCO to give .3 rep per week at equilibrium state	Calculated Dose Per Day (P.D./day)		Air and Water Concentrations (Without factor of safety)		
		VIA LUNGS	VIA G-I TRACT	CONTAMINATION VIA AIR		VIA WATER
				8 hr exp/day $10\ m^3$ air/8 hr	24 hr exp/day $20\ m^3$ air/24 hr	2.2 liters/day
	Q	$Q\frac{m}{f_L}$ μc/day	$Q\frac{m}{f_G}$ μc/day	$\frac{P.D./day}{10 \times 10^6 cc\ air}$ μc/cc air	$\frac{P.D./day}{20 \times 10^6 cc\ air}$ μc/cc air	$\frac{P.D./day}{2200\ ml\ water}$ μc/ml water
	(20)	(21)	(22)	(23)	(24)	(25)
1	1.37×10^{-1}	535	401	5.4×10^{-5}	2.7×10^{-5}	.18
2	1.55×10^{-2}	9.00	6.77	9×10^{-7}	4.5×10^{-7}	3.1×10^{-3}
3	8.66×10^{-4}	4.81	3.58	4.81×10^{-7}	2.4×10^{-7}	1.6×10^{-3}
4	3.04×10^{-4}	35.5	25.5	3.4×10^{-6}	1.7×10^{-6}	1.1×10^{-2}
5	1.2×10^{-3}	.713	.537	7.1×10^{-8}	3.6×10^{-8}	2.4×10^{-4}
6	1.47×10^{-2}	11.2	8.43	1.1×10^{-6}	5.6×10^{-7}	3.8×10^{-3}
7	3.42×10^{-3}	11.9	8.93	1.2×10^{-6}	6×10^{-7}	4.1×10^{-3}
8	1.55×10^{-3}	2.26	1.7	2.3×10^{-7}	1.2×10^{-7}	7.7×10^{-4}
9	5.6×10^{-4}	65.3	49.2	6.5×10^{-6}	3.3×10^{-6}	2.2×10^{-2}
10	$.95 \times 10^{-2}$	4.75×10^{-2}	3.56×10^{-2}	4.8×10^{-9}	2.4×10^{-9}	1.6×10^{-5}
11	1.24×10^{-3}	1.41	1.05	1.4×10^{-7}	7×10^{-8}	4.8×10^{-4}
12	7.42×10^{-4}	467	350	4.7×10^{-5}	2.4×10^{-5}	1.6×10^{-1}
13	6.68×10^{-4}	12.6	9.55	1.3×10^{-6}	6.5×10^{-7}	4.3×10^{-3}
14	2.24×10^{-3}	5.95	4.52	6×10^{-7}	3×10^{-7}	2.1×10^{-3}
15	5.96×10^{-4}	594	451	5.9×10^{-5}	3×10^{-5}	.2
16	4.3×10^{-3}	110	82.5	1.1×10^{-5}	5.5×10^{-6}	3.8×10^{-2}
17	1.39×10^{-1}	5.26	3.94	5.3×10^{-7}	2.7×10^{-7}	1.8×10^{-3}
18	1.43×10^{-3}	.302	.228	3×10^{-8}	1.5×10^{-8}	1×10^{-4}
19	4.3×10^{-3}	21.3	15.3	2.1×10^{-6}	1.1×10^{-6}	7×10^{-3}
20	6.3×10^{-2}	9×10^{-2}	6.7×10^{-2}	9.1×10^{-9}	4.5×10^{-9}	3.1×10^{-5}
21	6.48×10^{-3}	3.6×10^{-2}	2.7×10^{-9}	3.6×10^{-9}	1.9×10^{-9}	1.2×10^{-5}
22	1.97×10^{-3}	.26	.19	2.7×10^{-8}	1.3×10^{-8}	8.7×10^{-5}
23	3.66×10^{-3}	3.3×10^{-2}	2.4×10^{-2}	3.2×10^{-9}	1.6×10^{-9}	1.1×10^{-5}
24	1.5×10^{-3}	.11	8.4×10^{-2}	1.1×10^{-8}	5.7×10^{-9}	3.8×10^{-5}

Table III (Continued)

	Recommended Factor of Safety for Plant Personnel (26)	μc in SCO Q x m (27)	$\frac{Qm}{f_L}$ (28)	$\frac{Qm}{f_G}$ (29)	Weight Element In SCO gms c x m (30)	μc in total body (reference onl $\frac{Qm}{f_2}$ (31)
1	10^{-2}	9.6×10^3	1.28×10^4	9.6×10^3	7,000	9.6×10^3
2	10^{-2}	195	406	305	8,064	305
3	10^{-2}	60.6	80.8	60.1	68	60.1
4	10^{-2}	21.3	28.4	21.3	68	21.3
5	10^{-2}	8.4	14.2	10.7	550	10.7
6	10^{-2}	70.6	552	415	18	415
7	10^{-2}	29	160	120	25.5	119
8	10^{-2}	46.5	133	100	90	100
9	10^{-2}	16.8	48	36.2	90	36.2
10	10^{-2}	66.5	8.98	67.7	1,210	67.2
11	10^{-2}	8.68	11.7	8.77	1,210	8.77
12	10^{-2}	5.2	70.2	5.25	1,210	5.25
13	10^{-2}	1.13	103	78.3	2.89×10^{-3}	78.3
14	10^{-2}	3.8	346	263	2.89×10^{-3}	263
15	10^{-2}	1.01	92.2	70	2.89×10^{-3}	70
16	10^{-2}	21.5	51.6	38.7	2.5	38.7
17	10^{-2}	695	1.67×10^3	1.25×10^3	2.5	1.25×10^3
18	10^{-2}	2.43	17.1	12.9	.85	12.9
19	10^{-2}	7.3	66.5	47.8	15.3×10^{-3}	47.8
20	10^{-1}	1.26	6.29	4.66	8×10^{-3}	4.66
21	10^{-1}	.13	.648	.48	8×10^{-3}	.48
22	10^{-1}	3.94×10^{-2}	.197	.146	8×10^{-3}	.146
23	10^{-1}	7.32×10^{-2}	.366	.271	8×10^{-3}	.271
24	10^{-1}	3×10^{-2}	.149	.111	8×10^{-3}	.111

The preceding calculations are taken from C.H. Perry's communications to the Subcommittee on Permissible Internal Dose of the National Committee on Radiation Protection concerning:

I^{131}, letter dated August 26, 1949

Elements Common to Body Metabolism, October 12, 1949

Insoluble $U^{235}O_2$, dated November 4, 1949

Insoluble $U^{234}O_2$, dated November 7, 1949

Insoluble $U^{238}O_2$, dated November 8, 1949

Part II

Dusts of Insoluble and Soluble Compounds of Radiouranium
(U^{234}, U^{235}, and U^{238})

Dusts of Insoluble Compounds of Radiouranium

A. Introduction

The calculations which follow are based upon UO_2 dust experimental data. It is suggested that these calculations apply to all insoluble uranium dusts where the lung is the principal organ of retention.

Also, it is suggested that these calculations apply to all sizes of dust particles. The basis for this suggestion is that the following calculations are based upon 60%* of the breathed particulates being retained in the alveoli of the lungs. This figure is so close to 2/3, which is about the maximum retention in the alveoli that is possible, that we would be safe regardless of the particulate size.

As the particulates increase in size to sizes $> 1\mu$, there is more and more retention in the upper respiratory tract. Since these larger particles find their way to the G-I tract, the lung ceases to be the critical organ of retention. The fraction that reaches the bone, kidney or other critical organ, will depend upon the degree of solubility of the particular molecule.

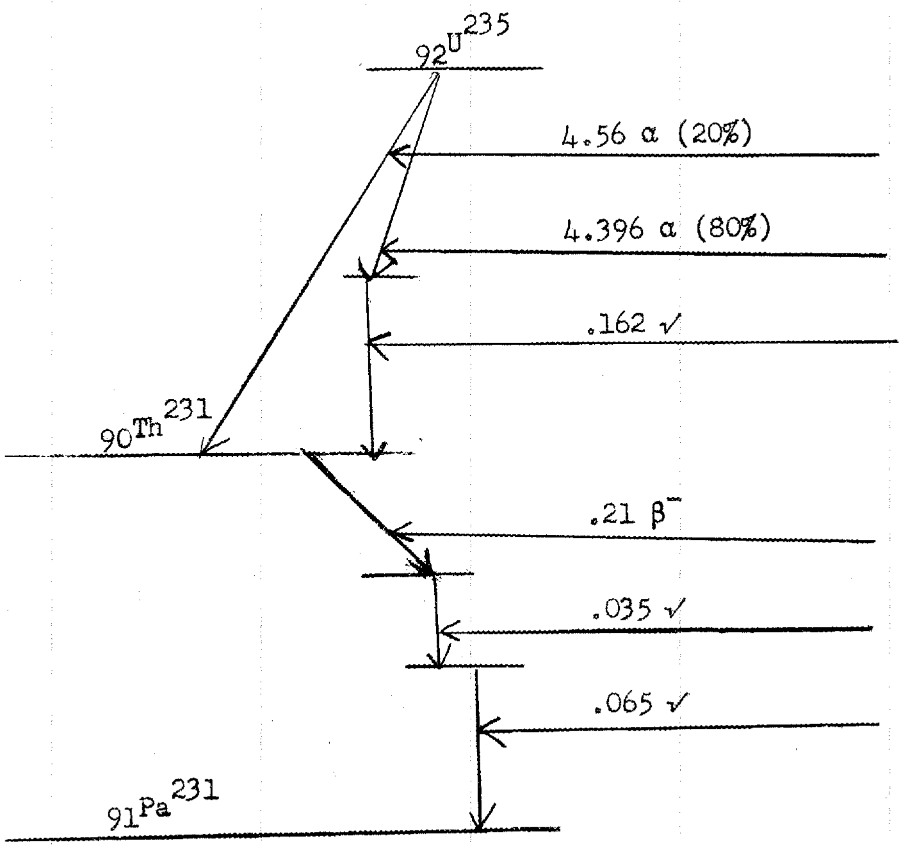
* The Chalk River Conference (See Part I) set 50% to lung and 50% to G-I tract for soluble and 25% in lung, 25% exhaled, and 50% to G-I tract for insoluble compounds.

It is suggested that if the particulates are known to be $\geq 1.5\mu$, or if there is reason to believe them to be, calculations be made on the basis of the bone or kidneys, etc., being the critical organ of retention. In any case, preliminary consideration should be given to a number of body organs to determine which is subjected to the greatest hazard from the particular radioisotope. Please refer to the soluble $U^{235}O_2$ section for further details.

Concerning the degree of non-uniformity of distribution of the dust in the alveoli, only research can supply the order of magnitude of this factor. We do know, however, that flocculation does occur, but we do not know to what extent it occurs. Therefore, we must select a factor (F_c) to account for this type of non-uniformity of distribution. You will note that $F_c = 3$ was used in the attached calculations. It is a simple matter to substitute an experimental value for F_c in the equations which follow, if desired.

Since each of the above isotopes are of the same element, their metabolism should be the same. Comparison of the calculated atmospheric concentration levels will show that a single level can be chosen to represent all three of the radioelements we are considering, provided that the chosen level is in terms of microcuries.

B. $U^{235}O_2$ Dusts



T_1r for $_{92}U^{235} = 8.91 \times 10^8$ y

T_2r for daughter $_{90}Th^{231} = 25.65$ h

T_3r for $_{91}Pa^{231} = 3.43 \times 10^4$ y (not used in these calculations).

In general, a subscript 1 refers to the parent; a subscript 2 refers to the daughter $_{90}Th^{231}$.

E_{eff}/dis for the Alphas

Since the alphas are monoenergetic, we have

$$E_{eff}/\text{dis}\ (\alpha\ s) = .2 \times 4.56 + .8 \times 4.396 = 4.429 \text{ Mev}$$

E_{eff}/dis for the gammas

We shall assume 12 cm as the effective thickness of the lungs.

$$E_{eff}/\text{dis}\ (.162\gamma) = .8 \times .162\ (1 - e^{-.0275 \times 12}) = .0364 \text{ Mev (Parent)}$$

$$E_{eff}/\text{dis}\ (.035\gamma) = .035\ (1 - e^{-.105 \times 12}) = .025 \text{ Mev (Daughter)}$$

$$E_{eff}/\text{dis}\ (.065\gamma) = .065\ (1 - e^{-.031 \times 12}) = .041 \text{ Mev (Daughter)}$$

E_{eff}/dis for the beta

$$b = .228,\ E_m = .21 \text{ Mev}$$

$$E_{eff}/\text{dis}\ (.21\ \beta^-) = .228 \times .21 = .048 \text{ Mev}$$

Percent contribution /disintegration made by each

For the parent

$$\frac{4.429 \times 100}{4.4654} = 99.18\% \text{ made by the alphas}$$

$$\frac{0364 \times 100}{4.4654} = 0.82\% \text{ made by the .162 gamma}$$

For the daughter

$\frac{.025 \times 100}{.114}$ = 21.93% made by the .035 gamma

$\frac{.041 \times 100}{.114}$ = 35.96% made by the .065 gamma

$\frac{.048 \times 100}{.114}$ = 42.11% made by the .21 beta

For the sake of completeness, all of the above contributions will be considered in the following.

Relative Biological Effectiveness (RBE)

During the Chalk River Meeting, it was agreed that absorbed energy from alpha particles contributes twenty times as much damage to tissue as do beta particles and photons (gamma and x-rays). This factor of 20 will manifest itself in the dose-rate equations which follow.

Total Dose Rate Due to Both Parent and Daughter

1) $$\frac{dr}{dt} = \left.\frac{dr}{dt}\right]_{1\alpha} + \left.\frac{dr}{dt}\right]_{1\gamma} + \left.\frac{dr}{dt}\right]_{2\beta\gamma} \text{ rep/day}$$

Because of the relative biological effectiveness of the α, β, and γ radiation, equation 1 becomes

2) $$\frac{.015}{7} = \left.\frac{dr}{dt}\right]_{1\alpha} + \frac{1}{20}\left.\frac{dr}{dt}\right]_{1\gamma} + \frac{1}{20}\left.\frac{dr}{dt}\right]_{2\beta\gamma} \text{ rems/day, where}$$

3) $$\left.\frac{dr}{dt}\right]_{1\alpha} = \frac{3.6 \times 10^{4} \times E_{1\alpha} \times Q_1 \times 10^{6} \times 4.8 \times 10^{-10} \times 86400}{36 \times 791} = 52.36\ E_{1\alpha} Q_1$$

4) $$20 \left.\frac{dr}{dt}\right]_{1\nu} = \frac{3.6 \times 10^{4} \times E_{1\nu} \times Q_1 \times 10^{6} \times 4.8 \times 10^{-10} \times 86400}{20 \times 32 \times 876} = 2.66\ E_{1\nu} Q_1$$

5) $$20 \left.\frac{dr}{dt}\right]_{2\beta\nu} = \frac{3.6 \times 10^{4} \times E_{2\beta\nu}\ Q_2 \times 10^{6} \times 4.8 \times 10^{-10} \times 86400}{20 \times 32 \times 876} = 2.66\ E_{2\beta\nu} Q_2$$

$$\frac{.015}{7} = 52.36\ E_{1\alpha}\ Q_1 + 2.66\ E_{1\nu} Q_1 + 2.66\ E_{2\beta\nu} Q_2$$

6) $$\frac{.015}{7} = Q_1\ (52.36\ E_{1\alpha} + 2.66\ E_{1\nu}) + Q_2\ (2.66\ E_{2\beta\nu})$$

where Q_1 = μc of parent/gm organ

Q_2 = μc of daughter/gm organ

<u>Development of the General Equation for N_c, the Total Number of Microcuries (μc) of Parent and of Daughter in the Organ at Any Time t</u>

The following symbols will be used:

N_1 = number of parent atoms present in organ at any time t

N_{1c} = number of parent μc present in organ at any time t

N_2 = number of daughter atoms present in organ at any time t

N_{2c} = number of daughter μc present in organ at any time t

λ_{1r} = radiological decay constant for the parent

λ_{1b} = biological decay constant for man's lung

λ_{1e} = effective decay constant for man's lung

λ_{2r} = radiological decay constant for the daughter

λ_{2b} = biological decay constant for man's lung

λ_{2e} = effective decay constant for man's lung

R_1 = number of parent atoms deposited/day in man's lung

R_{1c} = number of parent μc deposited/day in man's lung

k = constant of proportionality between the number of atoms and the number of μc

$N_c = N_{1c} + N_{2c}$ total μc present in organ at any time t

$Q = Q_1 + Q_2$ total μc/gm organ at any time t

m = weight of organ in gms.

7) $\frac{dN_1}{dt} = R_1 - \lambda_{1e}N_1$ change in number of parent atoms in organ per day

8) $\frac{dN_1}{dt} + \lambda_{1e}N_1 = R_1$ the solution of which is

$$N_1 e^{\int \lambda_{1e} dt} = \int R_1 e^{\int \lambda_{1e} dt} dt + C_1$$

$$N_1 e^{\lambda_{1e} t} = \frac{R_1}{\lambda_{1e}} e^{\lambda_{1e} t} + C_1$$

Solving for C_1, we have

when $t = 0$, $N_1 = 0$

$C_1 = \frac{R_1}{\lambda_{1e}}$, substituting, we have

$$N_1 e^{\lambda_{1e} t} = \frac{R_1}{\lambda_{1e}} e^{\lambda_{1e} t} - \frac{R_1}{\lambda_{1e}}$$

9) $N_1 = \frac{R_1}{\lambda_{1e}} (1 - e^{-\lambda_{1e} t})$

10) $\frac{dN_2}{dt} = \lambda_{1r}N_1 - \lambda_{2e}N_2$ change in number of daughter atoms in organ per day

11) $\frac{dN_2}{dt} + \lambda_{2e}N_2 = \lambda_{1r}N_1$ the solution of which is

$$N_2 e^{\int \lambda_{2e} dt} = \int \lambda_{1r} N_1 e^{\int \lambda_{2e} dt} dt + C_2$$

$$N_2 e^{\lambda_{2e} t} = \int \lambda_{1r} N_1 e^{\lambda_{2e} t} dt + C_2$$

9) But $N_1 = \frac{R_1}{\lambda_{1e}} (1 - e^{-\lambda_{1e} t})$ substituting, we have

$$N_2 e^{\lambda_{2e} t} = \int \frac{\lambda_{1r} R_1}{\lambda_{1e}} (1 - e^{-\lambda_{1e} t}) e^{\lambda_{2e} t} dt + C_2$$

$$N_2 e^{\lambda_{2e} t} = \frac{\lambda_{1r} R_1}{\lambda_{1e}} \left[\int e^{\lambda_{2e} t} dt - \int e^{(\lambda_{2e} - \lambda_{1e}) t} dt \right] + C_2$$

$$N_2 e^{\lambda_{2e} t} = \frac{\lambda_{1r} R_1}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e}} \int e^{\lambda_{2e} t} \lambda_{2e} dt - \frac{1}{\lambda_{2e} - \lambda_{1e}} \times \right.$$

$$\left. \times \int e^{(\lambda_{2e} - \lambda_{1e}) t} (\lambda_{2e} - \lambda_{1e}) dt \right] + C_2$$

$$N_2 e^{\lambda_{2e} t} = \frac{\lambda_{1r} R_1}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e}} \int e^{\lambda_{2e} t} - \frac{1}{\lambda_{2e} - \lambda_{12}} e^{(\lambda_{2e} - \lambda_{1e}) t} \right.$$

$$+ C_2$$

Solving for C_2, we have

when $t = 0$ then $N_2 = 0$

$$C_2 = \frac{\lambda_{1r}R_1}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} - \frac{1}{\lambda_{2e}} \right], \text{ substituting,}$$

we have

$$N_2 e^{\lambda_{2e}t} = \frac{\lambda_{1r}R_1}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(1 - e^{(\lambda_{2e} - \lambda_{1e})t}\right) - \frac{1}{\lambda_{1e}}\left(1 - e^{\lambda_{2e}t}\right) \right]$$

12) $$N_2 = \frac{\lambda_{1r}R_1}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right) \right],$$

the number of daughter atoms present in organ at any time t.

13) But $R_{1c} = k\lambda_{1r}R_1$, the number of parent μc deposited in organ per day

$$kN_2 = \frac{R_{1c}}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right) \right]$$

14) And $k\lambda_{2r}N_2 = N_{2c}$, the number of μc of daughter present in organ at any time t.

15) $$N_{2c} = \frac{\lambda_{2r}R_{1c}}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right) \right]$$

9) $$N_1 = \frac{R_1}{\lambda_{1e}} \left(1 - e^{-\lambda_{1e}t}\right)$$

16) But $k\lambda_{1r}N_1 = N_{1c}$, the number of μc of parent present in organ at any time t.

Therefore,

17) $$N_{1c} = \frac{k\lambda_{1r}R_1}{\lambda_{1e}} \left(1 - e^{-\lambda_{1e}t}\right)$$

18) But $k\,\lambda_{1r}R_1 = R_{1c}$. Therefore,

19) $$N_{1c} = \frac{R_{1c}}{\lambda_{1e}}\left(1 - e^{-\lambda_{1e}t}\right)$$

20) $$N_c = N_{1c} + N_{2c}$$

21) $$N_c = \frac{R_{1c}}{\lambda_{1e}}\left(1 - e^{-\lambda_{1e}t}\right) + \frac{2_r R_c}{\lambda_{1e}}\left[\frac{1}{\lambda_{2e} - \lambda_{1e}}\left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right)\right]$$

22) $$N_c = \frac{R_{1c}}{\lambda_{1e}}\left[1 - e^{-\lambda_{1e}t} + \frac{\lambda_{2r}}{\lambda_{2e} - \lambda_{1e}}\left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{\lambda_{2r}}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right)\right]$$

N_c = total number of μc of parent and daughter in the organ at any time t.

The relations between the N_c's and the Q's are

23) $$Q_1 = \frac{N_{1c}}{m} \qquad Q_2 = \frac{N_{2c}}{m}$$

Substituting the values of equation 23) in equation 6), we have

24) $$\frac{.015}{7} = \frac{R_{1c}}{m\,\lambda_{1e}}\left(1 - e^{-\lambda_{1e}t}\right)(52.36\, E_{1\alpha} + 2.66\, E_{1\nu}) + \frac{\lambda_{2r}R_{1c}}{m\,\lambda_{1e}} \cdot$$
$$\cdot\left[\frac{1}{\lambda_{2e} - \lambda_{1e}}\left(e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right)\right](2.66\, E_{2\beta\nu})$$

25) $$R_{1c} = \frac{.015m\,\lambda_{1e}}{7}\left\{\left(1 - e^{-\lambda_{1e}t}\right)(52.36\, E_{1\alpha} + 2.66\, E_{1\nu}) + \right.$$
$$+ \lambda_{2r}\left[\frac{1}{\lambda_{2e} - \lambda_{1e}}\left(e^{-\lambda_{2e}t} - e^{\lambda_{1e}t}\right) - \frac{1}{\lambda_{2e}}\left(e^{-\lambda_{2e}t} - 1\right)\right] \cdot$$
$$\left. \cdot\ (2.66\, E_{2\beta\nu})\right\}^{-1}$$

Equation 25) is the general equation which determines the number of parent μc deposited/day uniformly in the organ, which will give a permissible dose rate due to parent and daughter after time t.

Fraction (f_L) of UO_2 Breathed Which Goes to Lung

If one plots the "limits" listed in Table 6 of Report UR-67, one will note that when the air concentration of UO_2 dust is about 280 μg U/m^3 of air, the lungs and the pulmonary lymph nodes (PLN) have equal retentions per gm of fresh lung tissue. When the UO_2 dust concentration in air is less than 280 μg U/m^3, the lungs appear to have greater and greater retentions of UO_2 dust/gm lung tissue as compared to the PLN retention. In as much as we shall be dealing with very much smaller air concentrations than 280 μg U/m^3, the lung appears to be the proper organ of retention.

Since our calculations are based upon the experimental data and theoretical treatment of these data in UR-67 and Hatch and Hemeon's work, the calculation for P.D./day should be for particles having sizes averaging about 1.2 to 1.4 microns. However, since 60% retention closely approximates the maximum possible retention (2/3)* it is conceivable that we could use 60% for all particle sizes where the lung is considered to be the principal organ of retention. Therefore, let f_L = .6.

* Hatch and Hemeon, in their publication "Influence of Particle Size in Dust Exposure" (A paper presented before the Am. Ind. Hygiene Assn. at Buffalo, N.Y. meeting on May 1, 1947), concluded that about 60% by weight of the particles whose sizes range between 1.2 and 1.4 microns will be retained by the lungs. They estimate further that between 6 and 12% by weight of the dust breathed will be retained in the upper respiratory tract.

Concentration Factor F_c

We can be certain that the UO_2 dust will not be distributed uniformly in the lung. However, further research must be done to determine the extent of the non-uniformity. For our purpose we shall assume that the concentration factor $F_c = 3$.

Permissible Dose/day (P.D./day)

26) $$\text{P.D./day} \times f_L \times F_c = R_{1c}$$

27) $$\text{P.D./day} = \frac{R_{1c}}{f_L \times F_c} \ \mu c \ U^{235}O_2$$

Substituting the value of R_{1c} (equation 25) in equation 27, we have

28) $$\text{P.D./day} = \frac{.015\, m\, \lambda_{1e}}{7\, f_L\, F_c} \left\{ (1 - e^{-\lambda_{1e} t})(52.36\, E_{1\alpha} + 2.66\, E_{1\gamma}) + \right.$$
$$+ \lambda_{2r} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] \cdot$$
$$\left. \cdot \ (2.66\, E_{2\beta\gamma}) \right\}^{-1} \mu c$$

Equation 28) is the general equation for the P.D./day μc $U^{235}O_2$ dust which will give a permissible dose rate to the lung tissue after any time t.

Selection of m, the Effective Weight of the Lung

Within a close approximation the normal lung contains an equal weight of circulating blood. This blood is in intimate association with the alveolar tissue and therefore, absorbs about one-half of the expended energy. Since the blood is circulating and receives the radiation only a fraction of a second out of each minute of time, we may consider the lung, minus the blood, as the principal organ which is irradiated. However, since the blood absorbs about one-half of the total absorbed energy, we may include the weight of the blood, together with the weight of the lung when making our calculation. Our m then becomes

$m = 2000$ gms, which has the effect of increasing the P.D./day rate.

Selection of the Effective Decay Constants for Parent (λ_{1e}) and for Daughter (λ_{2e}) in Man's Lung Tissue

In UR-67, the half-life of UO_2 dust in dog's lungs, based upon the retention at the end of a year's exposure is suggested to be about 54 days. If based upon highest and lowest values of retention, the half-life range is 46-72 days.

Similarly the half-life for the PLN has a range of 73-365 days with a suggested average of 100 days.

Because of the lack of data concerning the basal metabolic rate of the dogs used in this experiment, I have assumed that the dog's rate is twice that of man. Therefore, this will have the effect of doubling the half-life of UO_2 in the lungs of man.

$$T_{1b} = 2 \times 54 \text{ days} = 108 \text{ days for man}$$

$$\lambda_{1e} = \frac{.693}{108} + \frac{.693}{3 \times 10^9} = .0064 + 0$$

$\lambda_{1e} = .0064$ the total decay constant for $U^{235}O_2$ in the lung of man.

Concerning the daughter $Th^{231}O_2$, it is assumed that its biological half-life in man's lung is the same as that of UO_2 in the lung. Therefore,

$$T_{2b} = 108 \text{ days for man}$$

$$\lambda_{2e} = \frac{.693}{108} + \frac{.693}{1.069} = .0064 + .648 = .6544$$

$\lambda_{2e} = .6544$ the total decay constant for $Th^{231}O_2$ in the lung of man.

<u>Substituting Selected Values, We Have</u>

<u>For t = 30 days</u>

$$R_{1c} = \frac{.015 \times 2000 \times .0064}{7} \left\{ \overline{.1747}\ (52.36 \times 4.429 + 2.66 \times .0364) + \right.$$

$$\left. + .648 \left[1.5432\ \overline{(-.8253)} - 1.528\ (-1) \right] \cdot (2.66 \times .114) \right\}^{-1}$$

$$R_{1c} = \frac{.0274}{40.58} = 6.75 \times 10^{-4} \text{ parent } \mu c \text{ deposited per day in organ.}$$

<u>For t = 90 days</u>

$$R_{1c} = .0274 \left\{ \overline{.4379}\ (232) + .648 \left[1.5432\ \overline{(-.5621)} - 1.528\ (-1) \right] \times (.303) \right\}^{-1}$$

$$R_{1c} = \frac{.0274}{101.72} = 2.7 \times 10^{-4} \text{ parent } \mu c \text{ deposited/day in organ.}$$

<u>For t = 365 days</u>

$$R_{1c} = .0274 \left\{ \overline{.9033}\ (232) + .648 \left[1.5432\ \overline{(-.0967)} - 1.528\ (-1) \right] \times (.303) \right\}^{-1}$$

$$R_{1c} = \frac{.0274}{210} = 1.3 \times 10^{-4} \text{ parent } \mu c \text{ deposited/day in organ}$$

For t = 3 years

$$R_{1c} = .0274 \left\{ \overline{.9991} \; (232) \; + .648 \left[1.5432 \; \overline{(-.009)} - 1.528 \; (-1) \right] \times (.303) \right\}^{-1}$$

$$= .0274 \left\{ 231.79 + .648 \left[1.514 \right] .303 \right\}^{-1}$$

$$= .0274 \left\{ 231.79 + .297 \right.$$

$$R_{1c} = \frac{.0274}{232.1} = 1.2 \times 10^{-4} \text{ Parent } \mu c \text{ deposited/day in organ}$$

For t = 30 years

$$R_{1c} = .0274 \left\{ \overline{1} \; (231.79) + .648 \left[1.5432 \; \overline{(-0)} - 1.528 \; (-1) \right] \; (.303) \right\}^{-1}$$

$$R_{1c} = \frac{.0274}{232.1} = 1.2 \times 10^{-4} \text{ Parent } \mu c \text{ deposited/day in organ}$$

Maximum Permissible Concentration in Air (MPC)

For 30 days

$$\text{P.D./day} = \frac{R_{1c} \text{ (30 days)}}{f_L \times F_c} = \frac{6.75 \times 10^{-4}}{.6 \times 3} = 3.75 \times 10^{-4} \; \mu c$$

$$\text{MPC (8 hr exp/day)} = \frac{3.75 \times 10^{-4}}{10^7} = 3.75 \times 10^{-11} \; \mu c \; U^{235}O_2\text{/cc air}$$

$$\text{MPC (24 hr exp/day)} = 1.88 \times 10^{-11} \; \mu c \; U^{235}O_2\text{/cc air}$$

For 90 days

$$P.D./day = \frac{R_{1c}\ (90\ days)}{f_L \times F_c} = \frac{2.7 \times 10^{-4}}{.6 \times 3} = 1.5 \times 10^{-4}\ \mu c$$

$$M.P.C.\ (8\ hr\ exp/day) = \frac{1.5 \times 10^{-4}}{10^7} = 1.5 \times 10^{-11}\ \mu c\ U^{235}O_2/cc\ air$$

$$M.P.C.\ (24\ hr\ exp/day) = 7.5 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ air$$

For 365 days

$$P.D./day = \frac{R_{1c}\ (365\ days)}{f_L \times F_c} = \frac{1.3 \times 10^{-4}}{.6 \times 3} = 7.2 \times 10^{-5}\ \mu c$$

$$M.P.C.\ (8\ hr\ exp/day) = \frac{7.2 \times 10^{-5}}{10^7} = 7.2 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ air$$

$$M.P.C.\ (24\ hr\ exp/day) = 3.6 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ air$$

For 3 years

$$P.D./day = \frac{R_{1c}\ (3\ years)}{f_L \times F_c} = \frac{1.2 \times 10^{-4}}{.6 \times 3} = 6.7 \times 10^{-5}\ \mu c$$

$$M.P.C.\ (8\ hr\ exp/day) = \frac{6.7 \times 10^{-5}}{10^7} = 6.7 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ air$$

$$M.P.C.\ (24\ hr\ exp/day) = 3.3 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ air$$

For 30 years

$$P.D./day = \frac{R_{1c}\ (30\ \text{years})}{f_L \times F_c} = \frac{1.2 \times 10^{-4}}{.6 \times 3} = 6.7 \times 10^{-5}\ \mu c$$

$$M.P.C.\ (8\ \text{hr exp/day}) = \frac{6.7 \times 10^{-5}}{10^7} = 6.7 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ \text{air}$$

$$M.P.C.\ (24\ \text{hr exp/day}) = 3.3 \times 10^{-12}\ \mu c\ U^{235}O_2/cc\ \text{air}$$

Table IV

Tabulation of Data on the Basis of Insoluble $U^{235}O_2$ Dust in the Lung

	DURATION OF EXPOSURE				
	t 30 days	t 90 days	t 1 year	t 3 years	t 30 years
Max Permissible Concentration (MPC) µc $U^{235}O_2$ Dust/cc Air (8 hr exp/day)	3.75×10^{-11}	1.5×10^{-11}	7.2×10^{-12}	6.7×10^{-12}	6.7×10^{-12}
Max Permissible Concentration (MPC) µc $U^{235}O_2$ Dust/cc Air (24 hr exp/day)	1.9×10^{-11}	7.5×10^{-12}	3.6×10^{-12}	3.3×10^{-12}	3.3×10^{-12}
Permissible Dose/day (P.D./day) µc $U^{235}O_2$ Dust = $R_{1c}/f_L F_c$	3.75×10^{-4}	1.5×10^{-4}	7.2×10^{-5}	6.7×10^{-5}	6.7×10^{-5}
R_{1c} = parent µc deposited uniformly/day in lung of man	6.75×10^{-4}	2.7×10^{-4}	1.3×10^{-4}	1.2×10^{-4}	1.2×10^{-4}

$$MCP = \frac{P.D./day}{\text{cc air breathed during working hours}}$$

$$R_{1c} = \frac{.015\ m\,\lambda_{1e}}{7} \left\{ (1 - e^{-\lambda_{1e}t})(52.36\ E_{1\alpha} + 2.66\ E_{1\gamma}) + \lambda_{2r} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e}t} - e^{-\lambda_{1e}t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e}t} - 1) \right] (2.66\ E_{2\beta\gamma}) \right\}^{-1}$$

f_L = .6 $\qquad$ F_c = 3 $\qquad$ $E_{1\alpha}$ eff/dis = 4.429 Mev

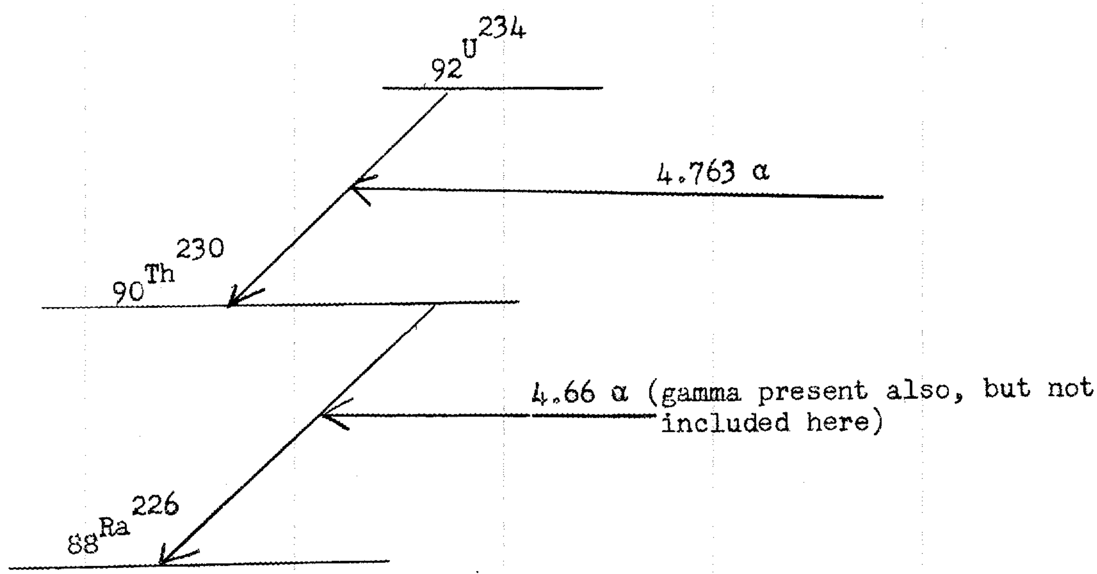
λ_{1e} = .0064 $\qquad$ λ_{2e} = .6544 $\qquad$ $E_{1\gamma}$ eff/dis = .0364 Mev

$\lambda_{1r} = \sim 0$ $\qquad$ λ_{2r} = .648 $\qquad$ $E_{2\beta\gamma}$ eff/dis = .114 Mev

T_{1b} = 108 days $\qquad$ T_{2b} = 108 days

Please note that no factor of safety has been applied to the above figures.

C. $U^{234}O_2$ Dusts



T_{1r} for $_{92}U^{234} = 2.35 \times 10^5$ y; $\lambda_{1r} \approx 0$

T_{2r} for daughter $_{90}Th^{230} = 8.0 \times 10^4$ y; $\lambda_{2r} \approx 0$

In general, the subscript 1 refers to parent; subscript 2 refers to daughter.

E_{eff}/dis

$E_{eff}/dis\ (U^{234}) = 4.763$ Mev

$E_{eff}/dis\ (Th^{230}) = 4.66$ Mev (Gamma not included)

Total Dose due to Parent and Daughter

1) $$\frac{dr}{dt} = \left.\frac{dr}{dt}\right]_{1\alpha} + \left.\frac{dr}{dt}\right]_{2\alpha} = \frac{.015}{7} \text{ rems/day}$$

2) $$\left.\frac{dr}{dt}\right]_{1\alpha} = 52.36\ E_1 Q_1$$

3) $$\left.\frac{dr}{dt}\right]_{2\alpha} = 52.36\ E_2 Q_2$$

$$\frac{.015}{7} = 52.36\ E_1 Q_1 + 52.36\ E_2 Q_2$$

$$\frac{.015}{7} = 52.36\ (E_1 Q_1 + E_2 Q_2)$$

4) But $Q_1 = \frac{N_{1c}}{m}$ $\qquad Q_2 = \frac{N_{2c}}{m}$

Substituting, we have

$$\frac{.015}{7} = 52.36\ \left(\frac{E_1 N_{1c}}{m} + \frac{E_2 N_{1c}}{m}\right)$$

5) But $N_{1c} = \frac{R_{1c}}{\lambda_{1e}} (1 - e^{-\lambda_{1e} t})$,

6) and $N_{2c} = \frac{\lambda_{2r} R_{1c}}{\lambda_{1e}} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right]$

Substituting, we have

7)
$$\frac{.015}{7} = 52.36 \left\{ \frac{E_1 R_{1c}}{m \lambda_{1e}} \left(1 - e^{-\lambda_{1e} t}\right) + \frac{E_2 \lambda_{2r} R_{1c}}{m \lambda_{1e}} \cdot \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}\right) - \frac{1}{\lambda_{2e}} \left(e^{-\lambda_{2e} t} - 1\right) \right] \right\}$$

Solving for R_{1c}, we have

8)
$$R_{1c} = \frac{.015\, m \lambda_{1e}}{7 \times 52.36} \left\{ E_1 \left(1 - e^{-\lambda_{1e} t}\right) + E_2 \lambda_{2r} \cdot \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} \left(e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}\right) - \frac{1}{\lambda_{2e}} \left(e^{-\lambda_{2e} t} - 1\right) \right] \right\}^{-1}$$

An inspection of equation 8 shows that the second term in the $\{\ \}$ is zero because $\lambda_{2r} \sim 0$. Therefore

9)
$$R_{1c} = \frac{.015\, m \lambda_{1c}}{7 \times 52.36\, E_1} \left(1 - e^{-\lambda_{1e} t}\right)^{-1}$$

9a)
$$R_{1c} = 1.100 \times 10^{-4} \left(1 - e^{-\lambda_{1e} t}\right)^{-1}$$

For $t = 30$ days $R_{1c} = 1.1 \times 10^{-4} \times 5.724 = 6.3 \times 10^{-4}$ μc/day deposited

$t = 90$ days $R_{1c} = 1.1 \times 10^{-4} \times 2.284 = 2.5 \times 10^{-4}$ μc/day deposited

t = 365 days $R_{1c} = 1.1 \times 10^{-4} \times 1.107 = 1.2 \times 10^{-4}$ μc/day deposited

t = 3 years $R_{1c} = 1.1 \times 10^{-4} \times 1.000 = 1.1 \times 10^{-4}$ μc/day deposited

t > 3 years $R_{1c} = 1.1 \times 10^{-4}$

Equation 9 is the general equation which determines the number of U^{234} μc deposited/day uniformly in the organ, which will give a permissible dose rate after any time t.

Permissible Dose per day P.D./day

10) $$\text{P.D./day} \times f_L \times F_c = R_{1c} \ \mu c$$

11) $$\text{P.D./day} = \frac{R_{1c}}{f_L F_c} \ \mu c \ U^{234}O_2 \text{ dust}$$

For t = 30 days $\text{P.D./day} = \dfrac{6.3 \times 10^{-4}}{.6 \times 3} = 3.5 \times 10^{-4} \ \mu c$

t = 90 days $\text{P.D./day} = \dfrac{2.5 \times 10^{-4}}{.6 \times 3} = 1.39 \times 10^{-4} \ \mu c$

t = 365 days $\text{P.D./day} = \dfrac{1.2 \times 10^{-4}}{.6 \times 3} = 6.67 \times 10^{-5} \ \mu c$

t = 3 years $\text{P.D./day} = \dfrac{1.1 \times 10^{-4}}{.6 \times 3} = 6.1 \times 10^{-5} \ \mu c$

t > 3 years $\text{P.D./day} = 6.1 \times 10^{-5}$

Maximum Permissible Concentration (MPC) in Air

8 hr exposure per day

For $t = 30$ days, $$MPC = \frac{3.5 \times 10^{-4}}{10^{7}} = 3.5 \times 10^{-11} \ \mu c/cc \text{ air}$$

$t = 90$ days, $$MPC = \frac{1.39 \times 10^{-4}}{10^{7}} = 1.39 \times 10^{-11} \ \mu c/cc \text{ air}$$

$t = 365$ days, $$MPC = \frac{6.67 \times 10^{-5}}{10^{7}} = 6.67 \times 10^{-12} \ \mu c/cc \text{ air}$$

$t = 3$ years, $$MPC = \frac{6.1 \times 10^{-5}}{10^{7}} = 6.1 \times 10^{-12} \ \mu c/cc \text{ air}$$

$t > 3$ years, $$MPC = \frac{6.1 \times 10^{-5}}{10^{7}} = 6.1 \times 10^{-12} \ \mu c/cc \text{ air}$$

24 hr exposure per day

For $t = 30$ days, $$MPC = \frac{3.5 \times 10^{-4}}{2 \times 10^{7}} = 1.8 \times 10^{-11} \ \mu c/cc \text{ air}$$

$t = 90$ days, $$MPC = \frac{1.39 \times 10^{-4}}{2 \times 10^{7}} = 7 \times 10^{-12} \ \mu c/cc \text{ air}$$

$t = 365$ days, $$MPC = \frac{6.67 \times 10^{-5}}{2 \times 10^{7}} = 3.3 \times 10^{-12} \ \mu c/cc \text{ air}$$

$t = 3$ years, $$MPC = \frac{6.1 \times 10^{-5}}{2 \times 10^{-7}} = 3 \times 10^{-12} \ \mu c/cc \text{ air}$$

$t > 3$ years, $$MPC = \frac{6.1 \times 10^{-5}}{2 \times 10^{-7}} = 3 \times 10^{-12} \ \mu c/cc \text{ air}$$

Internal Dose Determinations

Table V

Tabulation of Data on the Basis of Insoluble $U^{234}O_2$ Dust in the Man's Lung

	DURATION OF EXPOSURE				
	30 days	90 days	365 days	3 years	3 years
Maximum Permissible Concentration (MPC) $\mu c\ U^{234}O_2$ dust/cc air (8 hr exp/day)	3.5×10^{-11}	1.4×10^{-11}	6.7×10^{-12}	6.1×10^{-12}	6.1×10^{-12}
Maximum Permissible Concentration (MPC) $\mu c\ U^{234}O_2$ dust/cc air (24 hr exp/day)	1.8×10^{-11}	7×10^{-12}	3.3×10^{-12}	3×10^{-12}	3×10^{-12}
Permissible Dose/day (P.D./day) $\mu c\ U^{234}O_2$ dust = $R_{1c}/f_L F_c$	3.5×10^{-4}	1.4×10^{-4}	6.7×10^{-5}	6.1×10^{-5}	6.1×10^{-5}
R_{1c} = U^{234} μc deposited uniformly per day in lung of man	6.3×10^{-4}	2.5×10^{-4}	1.2×10^{-4}	1.1×10^{-4}	1.1×10^{-4}

$$\text{M.P.C.} = \frac{\text{P.D./day}}{\text{cc air breathed during working hours/day}}$$

$f_L = .6$ $\quad F_c = 3$ $\quad \lambda_{1b} = .0064 = \lambda_{1e}$

$$R_{1c} = \frac{.015\ m\ \lambda_{1e}}{7 \times 52.36\ E_1} \left(1 - e^{-\lambda_{1e} t}\right)^{-1}$$

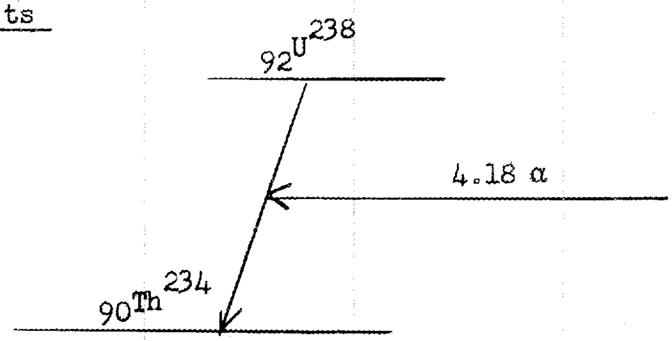
$\lambda_{1r} \approx 0$ $\quad T_{1b} = 108$ days $\quad E_{eff}/\text{dis} = 4.763$ Mev

$$R_{1c} = 1.100 \times 10^{-4} \left(1 - e^{-\lambda_{1e} t}\right)^{-1}$$

$$\text{P.D./day} = \frac{R_{1c}}{f_L \times F_c}$$

Please note that no factor of safety has been applied to the above figures, other than the factor F_c

D. $U^{238}O_2$ Dusts



$T_{1r} = 4.51 \times 10^9$ y

$\lambda_{1r} \approx 0$

$T_{1b} = 108$ days

$\lambda_{1b} = .0064$

$\lambda_e = .0064$

$E_{eff}/\text{dis} = 4.18$ Mev

Total Dose

1) $$\frac{dr}{dt} = 52.36\ E_1 Q_1 = \frac{.015}{7}\ \text{rems/day}$$

2) $$Q_1 = \frac{N_{1c}}{m}$$

3) $$N_{1c} = \frac{R_{1c}}{\lambda_{1e}}\left(1 - e^{-\lambda_{1e} t}\right)$$

and by substitution, we have

4) $$R_{1c} = \frac{.015\ m\ \lambda_{1e}}{7 \times 52.36\ E_1} (1 - e^{-\lambda_{1e} t})^{-1}$$

4a) $$R_{1c} = 1.25 \times 10^{-4} (1 - e^{-\lambda_{1e} t})^{-1}$$

Equation 4 is the general equation which determines the number of U^{238} μc deposited per day uniformly in the organ, which will give a permissible dose rate after any time t.

For t = 30 days, $R_{1c} = 1.25 \times 10^{-4} \times 5.724 = 7.2 \times 10^{-4}$ μc/day

t = 90 days, $R_{1c} = 1.25 \times 10^{-4} \times 2.284 = 2.9 \times 10^{-4}$ μc/day

t = 365 days, $R_{1c} = 1.25 \times 10^{-4} \times 1.107 = 1.4 \times 10^{-4}$ μc/day

t = 3 years, $R_{1c} = 1.25 \times 10^{-4} \times 1.000 = 1.25 \times 10^{-4}$ μc/day

t > 3 years, $R_{1c} = 1.25 \times 10^{-4}$ μc/day

<u>Maximum Permissible Dose per day (P.D./day)</u>

$$P.D./day \times f_L \times F_c = R_{1c}\ \mu c$$

$$P.D./day = \frac{R_{1c}}{f_L F_c}\ \mu c\ U^{238}O_2 \text{ dust}$$

For $t = 30$ days, $$\text{P.D./day} = \frac{7.2 \times 10^{-4}}{.6 \times 3} = 4 \times 10^{-4}\ \mu c$$

$t = 90$ days, $$\text{P.D./day} = \frac{2.9 \times 10^{-4}}{.6 \times 3} = 1.6 \times 10^{-4}\ \mu c$$

$t = 365$ days, $$\text{P.D./day} = \frac{1.4 \times 10^{-4}}{.6 \times 3} = 7.8 \times 10^{-5}\ \mu c$$

$t = 3$ years, $$\text{P.D./day} = \frac{1.25 \times 10^{-4}}{.6 \times 3} = 6.9 \times 10^{-5}\ \mu c$$

$t > 3$ years, $$\text{P.D./day} = 6.9 \times 10^{-5}\ \mu c$$

Maximum Permissible Concentration (MPC) in Air

8 hr exposure/day

For $t = 30$ days, $$\text{MPC} = \frac{4 \times 10^{-4}}{10^{7}} = 4 \times 10^{-11}\ \mu c\ U^{238}/\text{cc air}$$

$t = 90$ days, $$\text{MPC} = \frac{1.6 \times 10^{-4}}{10^{7}} = 1.6 \times 10^{-11}\ \mu c\ U^{238}/\text{cc air}$$

$t = 365$ days, $$\text{MPC} = \frac{7.8 \times 10^{-5}}{10^{7}} = 7.8 \times 10^{-12}\ \mu c\ U^{238}/\text{cc air}$$

$t = 3$ years, $$\text{MPC} = \frac{6.9 \times 10^{-5}}{10^{7}} = 6.9 \times 10^{-12}\ \mu c\ U^{238}/\text{cc air}$$

$t > 3$ years, $$\text{MPC} = 6.9 \times 10^{-12}\ \mu c\ U^{238}/\text{cc air}$$

24 hr exposure/day

For $t = 30$ days, $$MPC = \frac{4 \times 10^{-4}}{2 \times 10^{7}} = 2 \times 10^{-11} \ \mu c \ U^{238}/cc \ air$$

$t = 90$ days, $$MPC = \frac{1.6 \times 10^{-4}}{2 \times 10^{7}} = 8 \times 10^{-12} \ \mu c \ U^{238}/cc \ air$$

$t = 365$ days, $$MPC = \frac{7.8 \times 10^{-5}}{2 \times 10^{7}} = 3.9 \times 10^{-12} \ \mu c \ U^{238}/cc \ air$$

$t = 3$ years, $$MPC = \frac{6.9 \times 10^{-5}}{2 \times 10^{7}} = 3.5 \times 10^{-12} \ \mu c \ U^{238}/cc \ air$$

$t > 3$ years, $$MPC = \frac{6.9 \times 10^{-5}}{2 \times 10^{7}} = 3.5 \times 10^{-12} \ \mu c \ U^{238}/cc \ air$$

Table VI

Tabulation of Data on the Basis of Insolube $U^{238}O_2$ Dust in Man's Lung

	DURATION OF EXPOSURE				
	30 days	90 days	365 days	3 years	3 years
Maximum Permissible Concentration (MPC) μc $U^{238}O_2$ dust/cc air (8 hr exp/day)	4×10^{-11}	1.6×10^{-11}	7.8×10^{-12}	6.9×10^{-12}	6.9×10^{-12}
Maximum Permissible Concentration (MPC) μc $U^{238}O_2$ dust/cc air (24 hr exp/day)	2×10^{-11}	8×10^{-12}	3.9×10^{-12}	3.5×10^{-12}	3.5×10^{-12}
Permissible Dose/day (P.D./day) μc $U^{238}O_2$ dust $= R_{1c}/f_L F_c$	4×10^{-4}	1.6×10^{-4}	7.8×10^{-5}	6.9×10^{-5}	6.9×10^{-5}
$R_{1c} = U^{238}$ μc deposited uniformly per day in lung of man	7.2×10^{-4}	2.9×10^{-4}	1.4×10^{-4}	1.25×10^{-4}	1.25×10^{-4}

$$M.P.C. = \frac{P.D./day}{\text{cc air breathed during working hours/day}}$$

$$R_{1c} = \frac{.015\ m\ \lambda_{1c}}{7 \times 52.36\ E_1} (1 - e^{-\lambda_{1e} t})^{-1}$$

$f_L = .6$; $F_c = 3$; $\lambda_{1b} = .0064 = \lambda_{1e}$

λ_{1r} 0; $T_{1b} = 108$ days; $E_{eff}/dis = 4.18$ Mev

$$R_{1c} = 1.25 \times 10^{-4} (1 - e^{-\lambda_{1e} t})^{-1}$$

$$P.D./day = \frac{R_{1c}}{f_L \times F_c}$$

<u>Please note that no factor of safety has been applied to the above figures, other than the factor F_c</u>

Dusts of Soluble Compounds of Radiouranium

A. Introduction

Although bone is the principal organ of retention, bone is not considered here as being the organ which receives the radiation. Please note that active bone marrow (1500 gm) plus 300 grams of bone tissue which is in direct contact with the bone marrow and upon which is deposited the uranium, is the "organ" singled out to receive the alpha, beta and gamma radiation due to the presence of both parent and daughter.

Examination will show that, if bone were selected instead of the above "organ", an equivalent concentration factor ($F_c \sim 390$) would be required for bone. This figure is reasonable considering the fact that there are 7000 gms of bone and the uranium deposition is on the surface of a small portion of the bone.

It has been our custom to calculate permissible doses on the basis of a given number of rep/week, without taking into account the difference in radio-sensitivity of the various tissues. This procedure is most satisfactory for external doses, where any and all tissues may be irradiated. However, in the case of the internal emitter, the radiation is usually confined to a given tissue and the recognition of this difference in radio-sensitivity can be used to obtain a more meaningful permissible internal dose level.

As an example, one would suppose that adipose tissue could tolerate a higher dose rate than those tissue cells which are destined to become blood cells and bone cells. Roughly speaking <u>if</u> osteogenic cells, hemoblasts, and adipose tissue cells had the same radio-sensitivity, the destruction of the osteogenic cells and hemoblasts would pose quite a different problem than would the destruction of fat cells. In the former case, one would expect anemia to ensue without the accompaniment of an increased reticulocyte count. In the latter case, one would not expect such deleterious effects. Since one may reasonably suppose that fat cells can tolerate more radiation than can hemoblasts or osteogenic cells, it follows that there should be quite a difference in the radio-sensitivity of the tissue cells under consideration and the fat cells.

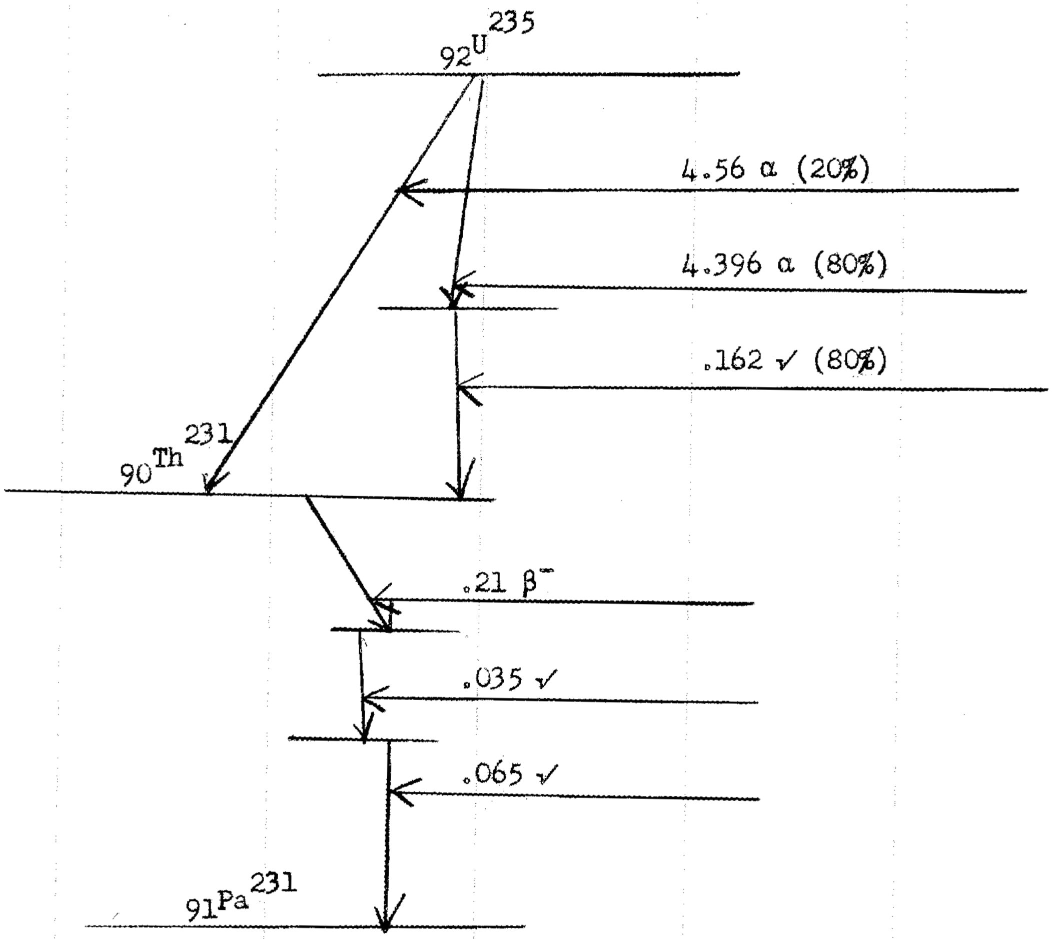
Although we have adhered closely in the past to a given radiation rate for all tissues alike, a vulnerability factor "V" has been used in the attached calculations. This factor states that a particular tissue can tolerate only 1/V the amount of radiation that the average tissue (or fat tissue) can tolerate. I have chosen V = 25 in the case of soluble uranium compounds. It is suggested that this factor be replaced by an experimental value when such information is available.

A concentration factor F = 100 has been chosen here. This factor may be removed also by multiplying my levels by 100. In this case, however, if bone is considered as being the vulnerable organ, the organ weight "m" must be changed accordingly. Also, a new concentration factor must be introduced to replace the value of the factor F_c which is used in the attached calculations.

The biological "half-time" of uranium in bone is estimated to be about 1500 days. This is based upon experiments at Rochester with rats, reported in UR-81, and UR-82, which indicate that the half-life is about 10 months in bone. Assuming that the metabolic rate of the rat is five times that of man, the biological half-life of uranium in the bone of man is estimated to be about 1500 days.

It is suggested that the Maximum Permissible Concentrations (MPC's) calculated for soluble U^{235} dusts be used for both U^{234} and U^{238} soluble dusts. The MPC levels, however, must be in terms of microcuries and not micrograms.

B. U^{235} Dusts



T_1r for $_{92}U^{235}$ = 8.91 x 10^8 y

T_2r for daughter $_{90}Th^{231}$ = 25.65 h

T_3r for $_{91}Pa^{231}$ = 3.43 x 10^4 y (not used in these calculations)

In general, a subscript 1 refers to the parent; a subscript 2 refers to the daughter $_{90}Th^{231}$.

E_{eff}/dis for the alphas

Since the alphas are monoenergetic, we have

$$E_{1\ eff}/\text{dis}\ (\alpha\text{'s}) = .2 \times 4.56 + .8 \times 4.396 = .912 + 3.517 = \underline{4.429\ \text{Mev}},$$

which is expended in osteogenic tissue which occurs within the inner bone surface in the epipyseal and metaphysical regions of bone, and the active (red) bone marrow which contacts the inner bone surfaces in these regions. Since the range in soft tissue (red B.M.) of 4.5 Mev alpha particles is about 40 μ and is about 20 μ in bone, and since the principal organ of retention, here considered, is the active bone marrow plus the precursors of bone and bone marrow tissues, we shall assume that the total alpha energy is expended within these tissues.

E_{eff}/dis for the gammas

It is estimated that the distance which the relatively soft gamma radiation will traverse in active bone marrow is about 4 cm. Using this thickness for absorption purposes, we have:

$$E_{eff}/\text{dis (Parent } .162\ \gamma) = .8 \times .162\ (1 - e^{-.0275 \times 4}) = .0135\ \text{Mev}$$

$$E_{eff}/\text{dis (Daughter } .21\ \beta^-) = bE_m = .228 \times .21 = .0479\ \text{Mev}$$

$$E_{eff}/\text{dis (Daughter } .035\ \gamma) = .035\ (1 - e^{-.105 \times 4}) = .0120\ \text{Mev}$$

$$E_{eff}/\text{dis (Daughter } .065\ \gamma) = .065\ (1 - e^{-.031 \times 4}) = .0076\ \text{Mev}$$

The beta energy (.0479 Mev) is expended in the same tissue as is the alpha energy. However, in the case of the beta particles, the equation $R = .407\ E^{1.38}\ gm/cm^2$, which expresses the range of beta particles in any medium, shows that the range for the average beta particle in soft tissue is about 65 μ, and about 33 μ in bone. It is assumed here that these ranges in bone and bone marrow are short enough to allow all the beta energy to be expended within our selected critical tissue.

A comparison of the parent effective energies per disintegration for alpha and gamma radiations show the following:

$$\frac{.0135\ \text{Mev}}{4.429\ \text{Mev}} = .003 = .3\%$$

The absorbed energy due to the parent gamma ray is about .3% of the absorbed energy due to the parent alpha. Therefore, this parent gamma absorbed energy will be neglected in the following calculations.

Relative Biological Effectiveness (RBE)

During the Chalk River meeting* it was agreed that absorbed energy from alpha particles should be considered to contribute twenty times as much damage to tissue as does beta particles and photons (x-rays and gamma rays). This factor of 20 will be used in the calculations which follow:

*Meeting September 29-30, 1949, of the United States, Canada, and British Representatives of the Radiation Protection Committees of their respective countries.

B. Derivation of Equations

Total Dose Rate Due to Both Parent and Daughter

1) $$\frac{dr}{dt} = \left.\frac{dr}{dt}\right]_{1\alpha} + \left.\frac{dr}{dt}\right]_{2\beta\gamma} \quad \text{reps/day}$$

Because of the RBE of the alpha, beta and gamma radiation, equation 1 becomes

2) $$\frac{.015}{7} = \left.\frac{dr}{dt}\right]_{1\alpha} + \left.\frac{1}{20}\frac{dr}{dt}\right]_{2\beta\gamma} \quad \text{rems/day, where}$$

3) $$\left.\frac{dr}{dt}\right]_{2\beta\gamma} = \frac{3.6 \times 10^4 \times E_{1\alpha} \times Q_1 \times 10^6 \times 4.8 \times 10^{-10} \times 86400}{36 \times 791} = 52.36\ E_{1\alpha}Q_1$$

4) $$20\left.\frac{dr}{dt}\right]_{2\beta\gamma} = \frac{3.6 \times 10^4 \times E_{2\beta\gamma}Q_2 \times 10^6 \times 4.8 \times 10^{-10} \times 86400}{20 \times 32 \times 876} = 2.66E_{2\beta\gamma}Q_2$$

Substituting, we have

5) $$\frac{.015}{7} = 52.36\ E_{1\alpha}Q_1 + 2.66\ E_{2\beta\gamma}Q_2$$

where Q_1 = μc of parent/gm of organ

Q_2 = μc of daughter/gm of organ

Obtaining equivalents for Q_1 and Q_2

6) $$Q_1 = \frac{N_{1c}}{m} \qquad Q_2 = \frac{N_{2c}}{m}$$

7) $$N_{1c} = \frac{R_1}{\lambda_{1e}} (1 - e^{-\lambda_{1e} t})$$

8) $$N_{2c} = \frac{\lambda_{2r} R_{1c}}{m \lambda_{1e}} (1 - e^{-\lambda_{1e} t})(52.36\ E_{1\alpha}) + \frac{\lambda_{2r} R_{1c}}{m \lambda_{1e}} \cdot$$

$$\cdot \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_2 t} - e^{-\lambda_1 t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] (2.66\ E_{2\beta\gamma})$$

Substituting these equivalents in equation 5, we have

9) $$\frac{.015}{7} = \frac{R_{1c}}{m \lambda_{1e}} (1 - e^{-\lambda_{1e} t})(52.36\ E_{1\alpha}) + \frac{2r R_{1c}}{m \lambda_{1e}} \cdot$$

$$\cdot \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_2 t} - e^{-\lambda_1 t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] (2.66\ E_{2\beta\gamma})$$

Solving for R_{1c}, we have

10) $$R_{1c} = \frac{.015\ m\ \lambda_{1e}}{7} \left\{ (1 - e^{-\lambda_{1e} t})(52.36\ E_{1\alpha}) + \right.$$

$$+ \lambda_{2r} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] \cdot$$

$$\left. \cdot (\underline{2.66}\ E_{2\beta\gamma}) \right\}^{-1}$$

Equation 10 is the general equation which determines the number of parent μc deposited/day uniformly in the organ, which will give a permissible dose rate, due to parent and daughter, after time t.

C. Details

Vulnerability Factor (V)

It is proposed at this time to recommend the use of a vulnerability factor (V), to be used in those cases where the radioactive deposition is such that more damage can be done to a specific tissue, with a given amount of radiation energy, than to the average body tissue. Tissues which contain precursors such as hemoblasts and osteoblasts which later become blood platelets and bone tissue respectively are examples of tissues which to my mind are more vulnerable than (say) fat tissue which represents about 18% of the total body weight.

The red bone marrow is very actively ingaged in supplying a large part of the blood for the body. It is reasonable to believe that a given amount of radiation can do relatively more damage to red bone marrow than the same amount of radiation can do to fat tissue. The examples are many, however, since we are dealing here with tissues composed of precursors of blood and bone tissues, it is sufficient to site only the above pertinent cases.

Since we do not have data which will evaluate the factor "V" for us, we must make a good guess and hope that future experiments will supply this much needed information. For a guess, I suggest that V be valued at 25.

The P.D./day calculations which follow will have V = 25. In those cases where one may have evidence to the contrary or a better guess in mind, it is requested that he apply his value of V to the final calculations.

Fraction (f_L) of Soluble Uranium Breathed which goes to Bone

The "Distribution Scheme" on page 88 shows that about 15% of the uranium, from soluble uranium compounds, goes to bone tissue in the adult. Therefore, f_L = .15 for adults. For uncontrolled areas where growing children are present, the factor f_L may be several times this magnitude. (Perhaps f_L approaches .6).

Concentration Factor (F_c) and Organ Weight (m)

Uranium is deposited in bone in greatest amounts where active calcification progresses. In long bone the most dense deposition occurs in the metaphysis under the periostium, and under the articular cartilage of the epiphysis. The deposition is on the surfaces of bone in these regions.

The selection of a concentration factor presupposes that the weight of the total organ is known or assumed. In this case, we are concerned with that fraction of the active (red) bone marrow which is literally in contact with the bone surfaces, and a very small thickness of bone ($\sim$ 20 μ) upon which is deposited the uranium.

<u>Distribution Scheme</u>. Based upon rat experiments with soluble uranium compounds. <u>ADULT</u> <u>NORMAL ACID-BASE SYSTEMS</u>

100% breathed →
- → 50% to alveoli → U^{+6} / U^{+4} (U^{+4} → U^{+6}) →
  - → 60% bicarbonate bound diffusible → blood →
  - → 40% protein bound non-diffusible (⇄ bicarbonate bound diffusible)
    - → ~$\frac{2}{3}$ to urine promptly (70% UR-81)
    - → ~$\frac{1}{5}$ to kidney for short time thence to urine (T_b = 4 days UR-82)
    - UR-82 → ~$\frac{1}{5}$ to skeleton for long time (T_b = 10 mo. UR-81)(30% - UR-81)
    - → balance to soft tissues for very short time thence redistributed and/or leaves via urine
- → 50% to Upper Respiratory tract → G-I tract →
  - → 49.5% to feces
  - → 0.5% to blood → above distribution

From this distribution scheme, we may arrive at the following assumption:

For all soluble uranium dust in air, .5 x ~ .3 = ~15% of all soluble uranium dust which is breathed by rats will find its way to the skeleton. This is based upon animal experiments having an undisturbed acid-base system. If the metabolic rate of the rat is 5 times that of man, the biological half-time of uranium in the bone of man should be about 5 x 10 months = 50 months.

References: UR-81, UR-82, Chalk River Meeting, September 29-30, 1949, Maynard and Hodge, N.N.E.S., Div. VI, Vol. 1A, Chapter V.

For the organ weight m, I have assumed 1500 gms for the red bone marrow plus 300 gms for bone. This will give m = 1800 gms.

For the concentration factor F_c, assume that the concentration is 100 times as great in a part of the critical tissue as it is in the "average" critical tissue which is comprised of 1800 gms of bone marrow and bone. Then $F_c = 100$.

It is suggested that this factor (F_c) be changed to agree with experimental data when these data become available.

Permissible Dose/day (P.D./day)

11) $$\text{P.D./day} \times f_L \times F_c \times V = R_{1c}\ \mu c$$

12) $$\text{P.D./day} = \frac{R_{1c}}{f_L \times F_c \times V} = \frac{R_{1c}}{.15 \times 100 \times 25} = \frac{R_{1c}}{375}\ \mu c$$

Substituting the value of R_{1c} (equation 10) in equation 12, we have

13) $$\text{P.D./day} = \frac{.015\, m\, \lambda_{1e}}{7 f_L F_c V} \left\{ (1 - e^{-\lambda_{1e} t})(52.36\, E_{1\alpha}) + \lambda_{2r} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] (2.66\, E_{2\beta\gamma}) \right\}^{-1} \mu c$$

Equation 13 is the general equation for the P.D./day μc via the lungs of soluble compounds of U^{235} dust which will give a "modified" permissible dose rate to the active bone marrow and adjacent bone tissue, herein defined, after any time t. (Modified by the factor V).

Selection of the Effective Decay Constants for Parent (λ_{1e}) and for Daughter (λ_{2e}) in Bone Tissue of Man

It is assumed that the parent U^{235} and the daughter Th^{231} have the same metabolic properties with respect to bone tissue. Further, that the biological half-times in bone are the same or are equivalent insofar as the P.D./day calculations are concerned.

Experiments with rats (UR-81) with soluble uranium compounds indicate a biological "half-life" in bone of about 10 months. If the metabolic rate of the rat is about five times that of man, we would expect the biological half-life in the bone of man to be about 5 x 10 months = 1500 days.

T_{1b} = 1500 days for man

$$\lambda_{1e} = \frac{.693}{1500} + \frac{.693}{3 \times 10^9} = .0005 + 0 = .0005,$$ Total decay constant for parent in the bone of man

T_{2b} = 1500 days for man

$$\lambda_{2e} = \frac{.693}{1500} + \frac{.693}{1.069} = .0005 + .6483 = .6488,$$ Total decay constant for daughter in the bone of man

Substituting Selected Values, We have

For t = 30 days

$$R_{1c} = \frac{.015 \times 1800 \times .0005}{7} \left\{ \overline{.0149} \times 231.46 + .6483 \cdot \right.$$

$$\left. \cdot \left[1.5425 \ \overline{(-.9851)} - 1.5413 \ \overline{(-1)} \right] \ .18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{3.452} = 5.6 \times 10^{-4} \ \mu c/\text{day to organ}$$

For t = 90 days

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{.0440} \times 231.46 + .6483 \left[1.5425 \ \overline{(-.9560)} - 1.5413 \ \overline{(-1)} \right] \right.$$

$$\left. \cdot \ 0.18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{10.19} = 1.9 \times 10^{-4} \ \mu c/\text{day to organ}$$

For t = 365 days

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{.1668} \times 231.46 + .6483 \left[1.5425 \ \overline{(-.8332)} - 1.5413 \ \overline{(-1)} \right] \right.$$

$$\left. \cdot \ .18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{38.64} = 5 \times 10^{-5} \ \mu c/\text{day to organ}$$

For t = 3 years

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{.4216} \times 231.46 + .6483 \cdot \right.$$

$$\left. \cdot \left[1.5425 \; \overline{(-\ .5784)} - 1.5413 \; \overline{(-\ 1)} \right] \; 0.18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{97.66} = 2 \times 10^{-5} \text{ } \mu c/\text{day to organ}$$

For t = 10 years

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{.8388} \times 231.46 + .6483 \left[1.5425 \; \overline{(-\ .1612)} - 1.5413 \; \overline{(-\ 1)} \right] \right.$$

$$\left. \cdot \; 0.18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{194.3} = 1 \times 10^{-5} \text{ } \mu c/\text{day to organ}$$

For t = 30 years

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{.9958} \times 231.46 + .6483 \left[1.5425 \; \overline{(-\ .0042)} - 1.5413 \; \overline{(-\ 1)} \right] \right.$$

$$\left. \cdot \; 0.18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{230.7} = 8.4 \times 10^{-6} \text{ } \mu c/\text{day to organ}$$

For $t = \infty$

$$R_{1c} = 1.929 \times 10^{-3} \left\{ \overline{1.0000} \times 231.46 + .6483 \cdot \right.$$

$$\left. \cdot \left[1.5425 \; (-\ .0000) - 1.5413 \; \overline{(-\ 1)} \right] 0.18 \right\}^{-1}$$

$$= \frac{1.929 \times 10^{-3}}{231.6} = 8.4 \times 10^{-6} \text{ μc/day to organ}$$

Maximum Permissible Dose/Day (P.D./day)

12) $$\text{P.D./day} = \frac{R_{1c}}{f_L \times F_c \times V} = \frac{R_{1c}}{.15 \times 100 \times 25} = \frac{R_{1c}}{375} \text{ μc } U^{235}$$

For t = 30 days

$$\text{P.D./day} = \frac{5.6 \times 10^{-4}}{375} = 1.5 \times 10^{-6} \text{ μc } U^{235}$$

For t = 90 days

$$\text{P.D./day} = \frac{1.9 \times 10^{-4}}{375} = 5.1 \times 10^{-7} \text{ μc } U^{235}$$

For t = 365 days

$$\text{P.D./day} = \frac{5 \times 10^{-5}}{375} = 1.3 \times 10^{-7} \text{ μc } U^{235}$$

For t = 3 years

$$\text{P.D./day} = \frac{2 \times 10^{-5}}{375} = 5.3 \times 10^{-8} \text{ μc } U^{235}$$

For t = 10 years

$$P.D./day = \frac{1 \times 10^{-5}}{375} = 2.7 \times 10^{-8} \ \mu c \ U^{235}$$

For t = 30 years

$$P.D./day = \frac{8.4 \times 10^{-6}}{375} = 2.2 \times 10^{-8} \ \mu c \ U^{235}$$

For $t = \infty$

$$P.D./day = \frac{8.4 \times 10^{-6}}{375} = 2.2 \times 10^{-8} \ \mu c \ U^{235}$$

Maximum Permissible Concentration in Air (MPC)

For t = 30 days

$$MPC \ (8 \text{ hr exp/day}) = \frac{1.5 \times 10^{-6}}{10^7} = 1.5 \times 10^{-13} \ \mu c \ U^{235}/\text{cc air}$$

$$MPC \ (24 \text{ hr exp/day}) = 7.5 \times 10^{-14} \ \mu c \ U^{235}/\text{cc air}$$

For t = 90 days

$$MPC \ (8 \text{ hr exp/day}) = \frac{5.1 \times 10^{-7}}{10^7} = 5.1 \times 10^{-14} \ \mu c \ U^{234}/\text{cc air}$$

$$MPC \ (24 \text{ hr exp/day} = 2.5 \times 10^{-14} \ \mu c \ U^{235}/\text{cc air}$$

<u>For t = 365 days</u>

$$\text{MPC (8 hr exp/day)} = \frac{1.3 \times 10^{-7}}{10^{7}} = 1.3 \times 10^{-14}\ \mu c\ U^{235}/cc\ air$$

$$\text{MPC (24 hr exp/day)} = 6.5 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

<u>For t = 3 years</u>

$$\text{MPC (8 hr exp/day)} = \frac{5.3 \times 10^{-8}}{10^{7}} = 5.3 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

$$\text{MPC (24 hr exp/day)} = 2.6 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

<u>For t = 10 years</u>

$$\text{MPC (8 hr exp/day)} = \frac{2.7 \times 10^{8}}{10^{7}} = 2.7 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

$$\text{MPC (24 hr exp/day)} = 1.3 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

<u>For t = 30 years</u>

$$\text{MPC (8 hr exp/day)} = \frac{2.2 \times 10^{-8}}{10^{7}} = 2.2 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

$$\text{MPC (24 hr exp/day)} = 1 \times 10^{-15}\ \mu c\ U^{235}/cc\ air$$

For $t = \infty$ years

MPC (8 hr exp/day) = 2.2×10^{-15} μc U^{235}/cc air

MPC 924 hr exp/day) = 1×10^{-15} μc U^{235}/cc air

Table VII

Tabulation of Calculations on Basis of Soluble U^{235} Dust in Bone of Man

	DURATION OF EXPOSURE						
	t 30 days	t 90 days	t 365 days	t 3 years	t 10 years	t 30 years	t years
MPC μc Soluble U^{235} dust per cc air (8 hr exp/day)	1.5×10^{-13}	5.1×10^{-14}	1.3×10^{-14}	5.3×10^{-15}	2.7×10^{-15}	2.2×10^{-15}	2.2×10^{-15}
MPC μc Soluble U^{235} dust per cc air (24 hr exp/day)	7.5×10^{-14}	2.5×10^{-14}	6.5×10^{-15}	2.6×10^{-15}	1.3×10^{-15}	1×10^{-15}	1×10^{-15}
P.D./day μc Soluble U^{235} dust	1.5×10^{-6}	5.1×10^{-7}	1.3×10^{-7}	5.3×10^{-8}	2.7×10^{-8}	2.2×10^{-8}	2.2×10^{-8}
R_{1c} = Parent μc deposited uniformly/day in bone of man	5.6×10^{-4}	1.9×10^{-4}	5×10^{-5}	2×10^{-5}	1×10^{-5}	8.4×10^{-6}	8.4×10^{-6}

$$\text{P.D./day} = \frac{R_{1c}}{f_L \times F_c \times V} = \frac{R_{1c}}{.15 \times 100 \times 25} = \frac{R_{1c}}{375}$$

$$R_{1c} = \frac{.015\, m \lambda_{1e}}{7} \left\{ (1 - e^{-\lambda_{1r} t})(52.36\, E_{1\alpha}) + \lambda_{2r} \left[\frac{1}{\lambda_{2e} - \lambda_{1e}} (e^{-\lambda_{2e} t} - e^{-\lambda_{1e} t}) - \frac{1}{\lambda_{2e}} (e^{-\lambda_{2e} t} - 1) \right] (2.66 E_{2\beta\nu}) \right\}^{-1}$$

$f_L = .15$ $F_c = 100$ $V = 25$ $E_{1\alpha}$ eff/dis = 4.429 Mev T_{1b} = 1500 days (bone)

$E_{2\beta\nu}$ eff/dis = .0675 Mev T_{2b} = 1500 days (bone)

$\lambda_{1r} = .0000$ $\lambda_{2r} = .6483$

$\lambda_{1b} = .0005$ $\lambda_{2b} = .0005$

$\lambda_{1e} = .0005$ $\lambda_{2e} = .6488$

Please note that no factor of safety has been applied to the above figures, except factors Fc and V

CHP:rr