THORIUM-232 IN HUMAN TISSUES:
METABOLIC PARAMETERS AND RADIATION DOSES*

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Abstract--Higher than environmental levels of ^{232}Th have been found in autopsy samples of lungs and other organs from four former employees of a Th refinery. Working periods of the subjects ranged from 3 to 24 years, and times from end of work to death ranged from 6 to 31 years. Concentrations of ^{232}Th in these samples and in tissues from two cases of non-occupational exposure were examined for compatibility with dosimetric models in Publication 30 of the International Commission on Radiological Protection (ICRP 1979a). The concentrations of ^{232}Th in the lungs of the Th workers relative to the concentrations in bone or liver were much higher than calculated from the model for class Y aerosols of Th and the exposure histories of the subjects, and concentrations in the pulmonary lymph nodes were much lower than calculated for three of the Th workers and both non-occupational cases. Least-squares fits to the measured concentrations showed that the biological half-times of Th in liver, spleen, and kidneys are similar to the half-time in bone instead of the factor of 10 less suggested in Publication 30, and the fractions translocated from body fluids were found to be about 0.03, 0.02, and 0.005, respectively, when the fraction to bone was held at the suggested value of 0.7. Fitted values of the respiratory parameters differed significantly between cases and the differences were ascribable to aerosol differences. Average inhalation rates calculated for individual Th workers ranged from 50

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to 110 Bq $^{232}\text{Th y}^{-1}$, and dose equivalents as high as 9.3 Sv to the lungs, 2.0 Sv to bone surfaces, and 1.1 Sv effective dose equivalent were calculated from the inhalation rates and fitted values of the metabolic parameters. The radiation doses were about the same when calculated from parameter values fitted with an assumed translocation fraction of 0.2 from body fluids to bone instead of 0.7.

Key words: thorium, human, metabolic models, internal dosimetry

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Current metabolic models of the behavior of non-colloidal Th in the body and of Th aerosols in the respiratory system are derived mostly from animal experiments. A report by Maletskos et al. (1969) on uptake from the GI tract is the only work on humans cited by the International Commission on Radiological Protection (ICRP) in proposing its metabolic model for Th in humans (ICRP 1979a*). The inhalation classes of Th aerosols were assigned from various animal experiments (Boecker et al. 1963; Ballou and Hursh 1972), and the model's values of parameters for the distribution and retention times of Th in internal organs were obtained from the work of Stover et al. (1960, 1965), who found that about 70% of ^{228}Th injected into beagle dogs went to long-term retention in bone and that 10% of the injected amount was quickly excreted. Newton et al. (1981) reported a biological half-life of at least 5000 days for the body content of ^{228}Th in a human subject, in agreement with the value Stover and coworkers found for bone in beagles. The ICRP30 compartmental model for Class Y aerosols with an activity median aerodynamic diameter (AMAD) of $1\text{ }\mu\text{m}$ is shown in Table 1, and the metabolic model for Th in body organs is shown in Table 2.

ICRP30 pointed out the need for more metabolic data to reduce the uncertainties in estimates of committed dose equivalent, and Kathren (1988) has reported apparent discrepancies between metabolic models and measurements of long-lived actinide nuclides in humans. In a recent paper on the distribution of ^{239}Pu in a human subject, McInroy et al. (1991) reported somewhat higher than predicted concentrations of Pu in soft tissues but rather good agreement with ICRP30 for the relative amounts in the skeleton and liver. Kathren (1988) emphasized that model predictions should be tested by comparison with actual measurements in human tissues after death, and this has already been done to some extent by studies of environmental Th in humans. Lucas and coworkers found an increase in the concentration of Th in bone with

*ICRP Publication 30, Part 1. Because of frequent reference to this publication, it will be designated as ICRP30 throughout this paper.

age (Lucas et al. 1970), an indication of long retention times in bone. Ibrahim and coworkers found that the amounts of ^{232}Th in lungs and bone were much greater than the amounts in other organs and concluded that inhalation was probably the principal route of intake of Th by non-occupationally exposed subjects (Ibrahim et al. 1983; Singh et al. 1983). In a recent study of environmental levels of Th at Bombay, Sunta et al. (1987) found organ concentrations of ^{232}Th similar to those previously reported but also found high concentrations in skeletal muscle, a body tissue not analyzed in other studies of Th in humans. The Bombay findings imply that less than 50% of ^{232}Th in the blood is transferred to bone in humans as opposed to the 70% found for single injections of ^{228}Th in beagles.

In a study of inhalation exposures at a thorium refinery, Mausner (1982) reported high concentrations of airborne ^{232}Th at the plant and high concentrations of ^{232}Th in autopsy samples from two former employees. Lucas and Stehney (1988) also found high concentrations of ^{232}Th in tissues from Mausner's subjects and from two other former employees of the refinery, and Stehney (1988) pointed out that ICRP30's metabolic model for Th was not compatible with observed distributions of Th among body tissues of the thorium workers. In the work reported here, measured concentrations of ^{232}Th in samples from the Th workers and from environmental cases were compared with concentrations calculated from the parameters shown in Tables 1 and 2, and new values of the parameters were fitted to the ratios of the measured concentrations. The fitted values were used to estimate the dose equivalents received by the individuals and to calculate annual limits on intake (ALIs) of ^{232}Th and ^{228}Th for comparison with current ICRP30 values.

MATERIALS

The determination of metabolic parameters from measurements of activity in autopsy samples requires knowledge of the duration of exposure of the subject and the interval from end of exposure to collection of samples. These are shown in Table 3 as the work dates and times from the end of each employment period to death for the four thorium workers for whom measurements

of ^{232}Th in the lungs and at least one other organ were obtained (Stehney and Lucas 1991). The Th plant produced Th and rare-earth compounds from monazite sands and other ores from the early 1930s to 1973 (Stehney et al. 1980). The other two cases described in Table 3 were obtained from a report on environmental levels of Th in autopsy samples from Grand Junction, Colorado (Wrenn et al. 1981). Wrenn and coworkers presented evidence that inhalation was the major route of intake of the ^{232}Th and ^{230}Th found in these samples. They considered the hard-rock miner to be a case of occupational exposure because concentrations of ^{230}Th in his tissues were much greater than the 50th percentile levels they found for the general population of Grand Junction. However, his ^{232}Th levels were similar to, or even lower than, those of the general population, so the present work treats this subject ("R-M") as a non-occupational exposure to ^{232}Th . For comparison, another case of non-occupational exposure, "G-J", was formulated in the present work as a composite of all the completely sampled males from the general population of Grand Junction. A case of what appeared to have been occupational exposure to low levels of Th as a uranium miner (Wrenn et al. 1981) could not be used because the time from the end of the work period to death was not made available. Wrenn and coworkers also reported Th measurements of samples from Washington, D.C., but no attempt was made in the present work to formulate cases from this population which included only three male cases of complete sampling and did not include samples of the spleen.

Table 4 gives the geometric means of the Th concentrations measured in autopsy samples from each case, the standard errors of the geometric means, and the number of samples analyzed for each case and type of tissue. If only one sample was analyzed, the measured concentration and the standard error of the measurement (SE) are shown. The data for the Th workers are from Stehney and Lucas (1991), and data for R-M and G-J are from Wrenn et al. (1981). The last set ("Normals") are estimates for a general male population that were obtained by pooling the measurements reported by Wrenn and coworkers for the 21 men in their two general populations (mean age 59). This composite was not considered suitable for study of metabolic parameters because the inclusion of incompletely sampled cases in the population means might have given a skewed

distribution of Th between organs. For similar reasons, the concentrations reported by Sunta et al. (1987) were not used as a population composite: their report gave no information about individual cases and included results for as many as 18 samples (for lungs) and as few as 6 samples (for pulmonary lymph nodes and for spleen). However, Sunta and coworkers reported almost equal geometric means for the concentrations of Th in samples of chest muscle and rib that may have come from the same subset of cases, since 10 samples of each type of tissue were analyzed. Implications of this finding were included in some of the calculations made during the course of the present work.

Geometric means were chosen as probably best representing pooled biological data from tissue samples and subjects, but this choice necessitated some arbitrary decisions in estimating the error of the geometric mean (GSE) when only one measurement of a tissue was available for a case. The GSE of a single measurement of lung or pulmonary lymph node (PLN) was assumed to be the same as the GSE found for the case with the largest number of analyzed lung samples, or estimated as the ratio of the measured value to the value minus the SE if this ratio was larger. The same rule was followed for single measurements of bone, liver, spleen, and kidney, except that the GSE of the largest number of analyzed bone samples was used. In order to relate the Th concentrations of samples from the Th workers solely to the work histories of those subjects, the concentrations for the Normals were subtracted from the concentrations measured in the workers, and the GSEs of the differences were estimated as the measured GSE multiplied by the ratio of the measured mean to the adjusted (net) mean. Since samples from the former Th workers had ²³²Th concentrations 10 to 1000 times greater than the normals, these adjustments for environmental exposure were trivial. The adjusted Th concentrations and GSEs, shown in Table 5, henceforth will be referred to as "measured" values. As can be deduced from Table 5, the GSE of lung samples of L2107 was used for three PLN samples, and the GSE of bone samples of L0770 was used for one bone sample and four samples of soft tissue.

Lung deposition and transfer of Th to other organs

ICRP30 (p. 56) provides a nomenclature and a general equation for the amount of activity in successive compartments after a single instantaneous deposition of unit activity in the first compartment of an originally activity-free system. However, the subjects of this paper were exposed to Th aerosols for periods of months or years (T_1) and autopsy samples were collected at some time (T_2) after the end of exposure, so equations for continuous intake had to be derived.

For continuous inhalation of unit activity per unit time, the increment of activity in the i^{th} compartment of a chain at T_1+T_2-t after a short intake period, dt , that occurred at time t after the start of intake will be the same as the amount resulting from instantaneous deposition of a quantity numerically equal to $DFdt$ in a compartment of the respiratory system with deposition fraction D and compartmental fraction F . From eqn (A.2) of ICRP30, the increment of activity is then

$$dq_i = \left[\prod_{k=1}^{i-1} \lambda_{(k,k+1)} \right] \sum_{k=1}^i \left[\frac{DFdt e^{-(\lambda_k + \mu)(T_1+T_2-t)}}{\prod_{p=1, p \neq k}^i (\lambda_p - \lambda_k)} \right], \quad (1)$$

where: $\lambda_{(k,k+1)}$ is the rate constant for transfer of material from compartment k to compartment $k+1$; λ_k is the rate constant for loss of material from compartment k ; μ is the radioactive decay constant of the radionuclide; Σ and Π are the sum and product, respectively, of the designated quantities; and $\Pi=1$ when $i=1$.

Integration of eqn (1) between 0 and T_1 then provides the following expression for the quantity of activity in the i^{th} compartment of the chain at time T_2 after the end of an inhalation period of duration T_1 :

$$Q_d = DF \left[\prod_{k=1}^{i-1} \lambda_{(k, k+1)} \right] \sum_{k=1}^i \left\{ \frac{[1 - e^{-(\lambda_k + \mu) T_1}] e^{-(\lambda_k + \mu) T_2}}{(\lambda_k + \mu) \prod_{p=1, p \neq k}^i (\lambda_p - \lambda_k)} \right\} . \quad (2)$$

Eqn (2) was incorporated into computer programs to calculate the amounts of Th per unit intake rate expected in the body organs and tissues of each subject. For subjects with multiple exposures, the activities calculated for each T_1, T_2 pair were summed to obtain the total amounts. Compartments e, f, g, and h (Table 1) were summed to provide the amount expected in the pulmonary region (lungs), and compartments i and j were summed for the PLN. The contributions of all the compartments (a to i) were summed to provide the amounts expected to be transferred to the internal organs. The only approximation made was to neglect the hold-up time of a few hours in the upper gastrointestinal tract prior to transfer of a small fraction of the Th in the small intestine to body fluids. These equations were used to calculate expected ratios of activities in body organs and tissues in order to fit the model parameters to the measured ratios, so the actual rate of intake did not have to be known. Although it was necessary to make the unrealistic assumption that each subject's rate of intake was constant during his periods of exposure, this should not have greatly affected comparisons of calculated activities with measured activities for subjects with long time periods of exposure and/or post-exposure, because fluctuations about their average rates would have had little effect on the amounts of Th in their body tissues at the time of autopsy.

Expected activity concentrations

The basic experimental data available for this work consisted of determinations of activity concentration, i.e., the amount of radioactivity in a tissue sample divided by the fresh sample weight. The expected values of these quantities for unit intake rates were estimated by dividing the calculated organ activities (eqn 2) by the organ masses for Reference Man that

are set out in Table 6 (ICRP 1975, ICRP 1979a). For the skeleton, the wet fat-free mass (8000 g) was used, because this condition most closely resembles the type of bone sample ordinarily used for laboratory measurements (Wrenn et al. 1981). For the same reason, no attempt was made to distinguish between mineralized cortical and trabecular bone, both of which "are more or less present in all bones" (ICRP 1975, p 66). Since the skeletal transfer fraction is defined for material translocated from body fluids to the 5000 g of mineralized bone, it is reasonable to consider the other 3000 g of the wet mass as part of the "remainder of the body" that contains the Th not immediately excreted or translocated to specified organs from the body fluids. For this reason, a fraction (3000 divided by the remainder mass) of the activity calculated for the remainder was added to the activity calculated for mineralized bone, before dividing by 8000 to obtain the calculated activity concentration of samples of bone. Furthermore, the ICRP30 metabolic models do not explicitly include translocation of radionuclides from the body fluids to tissues that comprise the respiratory system, so part of the remainder mass should be attributed to the tissues that comprise the lungs and lymph nodes. Accordingly, the activity concentration calculated for the remainder mass was added to the concentrations calculated for lungs and for lymph nodes in order to obtain the value to be used for comparison with the measured activity concentrations of lungs and lymph nodes. It should be noted that for long-lived radionuclides quickly removed from the respiratory passages of the lungs, the radioactivity of "remainder" tissue might persist in lung tissue long after the passages have cleared. (This treatment visualizes the respiratory system as a porous bag and adds the radioactivity of the bag material to the radioactivity inside the bag.)

Dose equivalents

The methods and assumptions of ICRP30 were used to calculate radiation doses from inhalation of initially pure ^{232}Th and subsequent growth of the daughters. General equations were derived for the activity of the j^{th} member of a decay chain in the i^{th} compartment at time T_2 after the end of continuous intake of the first member into the first compartment during time period T_1 .

(Appendix A). For inhalation of unit activity of the parent nuclide per unit time, the deposition rate in a respiratory-system compartment with regional fraction D_1 and compartmental fraction F_1 is numerically equal to $D_1 F_1$. From eqn (A.8), the number of transformations of the j^{th} nuclide in the i^{th} compartment during the entire period of $T_1 + T_2$ is then given by

$$U_i^j(0, T_1 + T_2) = D_1 F_1 \left[\prod_{k=1}^{i-1} \lambda_{(k, k+1)} \right] \left[\frac{\mu_j}{\mu_1} \prod_{m=1}^{j-1} \mu_{(m, m+1)} \right] \\ \times \sum_{k=1}^i \left| \sum_{m=1}^j \left\{ \frac{\left(\frac{T_1}{(\lambda_k + \mu_m)} - \frac{[1 - e^{-(\lambda_k + \mu_m) T_1}] e^{-(\lambda_k + \mu_m) T_2}}{(\lambda_k + \mu_m)^2} \right)}{\left[\prod_{p=1, p \neq k}^i (\lambda_p - \lambda_k) \right] \left[\prod_{r=1, r \neq m}^j (\mu_r - \mu_m) \right]} \right\} \right|, \quad (3)$$

where: U_i^j is the number of transformations of the j^{th} member of the decay chain in the i^{th} compartment; $\lambda_{(k, k+1)}$ is the rate constant for transfer from compartment k to compartment $k+1$; $\mu_{(m, m+1)}$ is the rate constant for transformation from species m to species $m+1$; and λ_k and μ_m are rate constants for transfer out of compartment k and for radioactive decay of species m , respectively.

Details of the calculation of dose equivalents and dosimetric data for the ^{232}Th and ^{228}Th decay chains are given in Appendix B of the present work. From eqn (4.7) of ICRP30, the dose equivalent in target T is given by

$$H_T = 1.6 \times 10^{-10} \sum_S \sum_j [U_S^j \text{SEE}(T-S)_j] \text{ Sv}, \quad (4)$$

where: 1.6×10^{-10} is a factor to convert from MeV g^{-1} to J kg^{-1} ; the summation in S is over all sources irradiating the target organ; the summation in j is over all radionuclides in source S ; U_S^j is the number of transformations of

t_j is j^{th} radionuclide in S; and $SEE(T \leftarrow S)_j$ is the specific effective energy (MeV $g^{-1}tr^{-1}$) absorbed in target T from transformations of radionuclide j in S.

Fitting procedures

To determine how well a set of metabolic parameters agreed with laboratory measurements of Th in the body tissues of a subject, the measured distribution in the body was compared with the distribution calculated from the parameter values and the exposure history of the subject. More specifically, the ratios of the concentrations measured in body tissues from an individual were compared with the ratios calculated for the same tissues. As indicated below, these comparisons were incorporated into fitting routines in order to obtain parameter values for the ICRP30 dosimetric models that fitted individual cases better than the values given in ICRP30.

The ICRP30 dosimetric model for the respiratory system was modified into the working model with 8 adjustable parameters that is displayed in Table 7. Since the autopsy tissues provided no direct information on the deposition behavior of the aerosols inhaled by the subjects, the regional deposition factors (D) in the working model were based on data in ICRP30 (p. 24) which indicate that the total fraction deposited in the respiratory system is about 0.8 ± 0.2 for particle sizes of 0.2 to 10 μm and that the fraction deposited in the TB region is constant at 0.08 over the same range of particle sizes. The fraction of Th deposited in the NP region that goes directly to body fluids was assumed to be equal to that in the TB region, but this fraction was made adjustable to allow for the possibility that these regions might contribute significantly to the amount of Th in the internal organs. In addition, removal half-times of a day or less in the ICRP30 models were kept at the ICRP30 values, because actual values of a few days or less would have had little effect on the long-term distribution of Th in the cases under study. Among parameters affecting the deposition of Th within the body (Table 2), the ICRP30 values for the retention time in bone ($T_{SK}=8000$ d), transfer from the small intestine to body fluids ($f_1=0.0002$), and the fraction quickly excreted from body fluids (0.1) all seem to be at least qualitatively well

established, so these parameter values were retained and kept constant in the working model.

The ICRP30 value of $f_2' = 0.7$ for the fraction of Th transferred from body fluids to bone was also assumed for most of the calculations. However this value had been obtained from the work of Stover and coworkers on the metabolism of ^{228}Th injected into beagles (Stover et al. 1960, 1965), and the recent report by Sunta et al. (1987) indicates that the fraction of ^{232}Th going to bone may be much smaller in humans. Sunta and coworkers suggested that the ratio of Th in skeletal muscle to Th in the skeleton was about 2.9 on the basis of the mean concentrations they found in autopsy samples. The relative values of f_2' for muscle and bone deduced from this ratio would depend on the relative values of the retention half-times: e.g., 2.9 if the half-times are equal, and about 2.0 if the half-time in muscle is twice that in bone and the subjects were 50 years old at death. In order to evaluate the effect of a smaller transfer fraction for bone, supplementary calculations were made with fixed f_2' values of 0.2 for bone (5 kg), 0.5 for skeletal muscle (28 kg), and 0.2 for the remainder of body mass (37 kg). Fits to muscle could not be made directly because no samples of muscle were analyzed for the cases suitable for the calculations, but the effect on the other parameters could be evaluated.

Limiting the adjustable parameters to the 8 indicated respiratory parameters (Table 7) plus 2 each for liver, spleen and kidneys still leaves more variables than the number of independent organ ratios, so unique fits and estimates of the statistical significance of the fits cannot be obtained from least-squares analyses of individual cases. However, an objective and consistent fitting procedure, such as described below, should find parameter values that reflect differences in both the long-term metabolic behavior of the aerosols to which the individuals were exposed and the distribution of Th among body organs.

An iterative fitting procedure was used in which the best set of parameters in each cycle was chosen on the basis of the closest fit of the calculated organ ratios to the measured ratios. All organs were given equal weight in the fitting routine by use of all of the organ ratios available (15

ratios for a case having a complete set of 6 measured organs), but only 5 or fewer of the ratios were independent for a given case. The variable parameters were assigned low, central, and high values in each cycle, and comparisons of calculated and measured ratios were made for the three values of each parameter while the other parameters were held constant at their central values of the cycle. The criterion of goodness-of-fit was a chi-square statistic, i.e., the sum of the squares of the differences between the measured and calculated ratios divided by the variances of the measured ratios. This criterion was a useful means of identifying parameter values that gave good agreement between calculated and measured ratios, but no statistical significance could be attached to the values of chi-square when the number of degrees of freedom was less than one. Because geometric means were used for the measured quantities, the chi-squares were calculated in log form, i.e.,

$$\frac{[\log(\text{ratio of geometric means}) - \log(\text{ratio of calculated concentrations})]^2}{[\log(\text{GSE of ratio of geometric means})]^2}$$

Except for the transfer fraction from body fluids to liver, the central estimate for each variable in the first cycle was the ICRP30 value, and the other two estimates were 10% less and 10% more than the central value. The central estimate for the transfer fraction for liver in the first cycle was set equal to its mass fraction of "remainder" activity in order to put it on the same basis as the fractions for spleen and kidneys. The estimates in the first cycle were the same for all of the subjects. The value that provided the best fit of the three became the central estimate of that variable in the next cycle. If the previous central value was retained, the other estimates were assigned values halfway to the previous outer estimates. If the low value had been selected as the new central value, the new low estimate was 10% less, and the new high estimate was halfway between the previous low and central values. If the high value had been selected, the new high estimate was 10% greater, and the new low estimate was halfway between the previous central and high values. This process was continued for 200 iterations or until the chi-square values of successive cycles differed by less than 1 part

in 10^8 ; at this point, the calculated ratios of the organ concentrations usually differed from the measured ratios by less than one percent.

Algorithms were written into the program to ensure that loss-rate constants in a chain did not become equal during the fitting routine. If any of the estimates of the rate constant being fitted attained a value within 1% of another rate constant in the same chain, its value was increased or decreased by 3% in order to allow it to move past the value of the latter. The accuracy of the program itself was checked by numerous hand calculations and by comparison of output values of committed dose equivalents for ^{232}Th with those given by ICRP (ICRP 1979b). With 16 potentially adjustable parameters, each cycle required as many as 48 calculations of the concentration of Th in lungs, lymph nodes, bone, liver, spleen, and kidneys. Thus, several thousand model calculations had to be made for each of the several variants of the working model examined in the course of this work.

RESULTS AND DISCUSSION

Comparison of autopsy data with ICRP30 metabolic models

In Table 8, the ratios of the measured concentrations of Th in lungs, lymph nodes, liver, spleen, and kidneys to the measured concentration of Th in bone are compared with the corresponding ratios calculated from the parameter values shown in Tables 1 and 2 for the ICRP30 dosimetric models. The value displayed for each subject (except L2107) under each organ heading is the measured ratio of organ concentration to bone concentration divided by the ratio calculated for the exposure history of that case, and the GSE of the measured ratio is shown below each value. Ratios to lungs are shown for L2107, because no measurements of Th in bone of this subject were available. If the measured and calculated ratios were in good agreement, then these ratios of ratios would have values close to unity to within the limits implied by the GSEs. Instead, a wide range of values is seen for every case, and some values differ from unity by factors of more than a hundred. Similar results were obtained for particle sizes with AMAD values of $0.1\ \mu\text{m}$ to $20\ \mu\text{m}$. The very high ratios for lungs in the Th workers were even higher when the

concentration of Th in remainder tissue was not included in the calculation of the activities, and the measured ratio divided by the calculated ratio was higher for all organs when the calculated bone concentration was obtained by dividing the calculated Th content of the skeleton by the mass of the mineralized skeleton (5000 g) instead of 8000 g (v. supra).

Examination of Table 8 provides some insight into relationships between the measured and calculated activities of the several types of samples. Since a value greater than one means that the calculated ratio was lower than the measured ratio, it is evident that the Th concentrations calculated for the lungs of the Th workers from the ICRP30 parameter values were too low and/or that the calculated bone concentrations were too high. Similarly, the high values for liver, spleen, and kidneys imply that the activities calculated for these organs were too low and/or that the calculated bone activities were too high. One interpretation of the ratios shown for L2107 is that the lung activity calculated for this subject was too small. The parameter values obtained by least-squares fits (described below) are consistent with these observations; the Th activities calculated with the ICRP30 parameters were too small for the liver, spleen, and kidneys of all the subjects and much too small for the lungs of the Th workers.

Fitted values of parameters for the body organs

Table 9 displays two sets of fitted parameters obtained for internal organs when the skeletal parameters were held at $F_{sk}=0.7$ and $T_{sk}=8000$ d. In both sets, the F_s and T_s of liver, spleen, and kidneys were allowed to vary, but the T_s were allowed to have different values in the first set and required to have a common value in the second set. The starting values for the fitting routines were set equal to the organ-mass fractions of remainder activity (0.0055, 0.00055, and 0.00095 for liver, spleen, and kidneys, respectively) and 700 d for the half-times of all three organs. Results with starting and fixed liver parameters of 0.04 and 8000 d are shown for subject L2107 for whom no measurements of bone were available. The table shows that half-times much greater than 700 d and transfer fractions greater than the organ-mass fractions of remainder activity, but much less than F_{sk} , were needed to fit

the observed distributions of Th. The transfer fractions of spleen and kidneys varied somewhat between cases, but the value for liver was close to the ICRP30 value of 0.04 for all the cases. The extraordinarily high values for the half-times of the spleen for some of the cases simply reflect the fact that the initial parameter values greatly underestimated the measured spleen activities, and the fitting procedure found not only higher values for the transfer fraction but also attained half-time values corresponding to virtually no loss of Th from the spleen.

From inspection of Table 9, one may reasonably conclude that the liver, spleen, and kidneys have long retention half-times, possibly similar to the value of 8000 d that was used for skeleton. Table 10 shows the fitted values that were obtained for the transfer fractions when the half-times of the four internal organs were fixed at 8000 d and F_{sk} was fixed at 0.70. The measured skeletal concentrations, without subtraction of environmental background, are also shown. Although an inverse relationship between half-time and the fitted values of transfer fraction is evident from comparison of the values for each subject in Table 10 with the values previously obtained for him, the transfer fractions obtained with half-times of 8000 d are not much different from those obtained when the fitted half-times were much greater. Transfer fractions of about 0.04 for liver were obtained for all of the subjects except L2932, but the Th workers appear to have higher values for spleen and possibly lower values for kidneys than those obtained for the non-occupational cases. The mean and standard deviation of the liver transfer fractions obtained for the five subjects with measured bone concentrations are 0.031 ± 0.010 .

It has been suggested that the deposition of Th on bone surfaces may be limited by the capacity of the deposition sites (Stover et al. 1960) or because of formation of colloidal hydrolysis products (Stover et al. 1962). If so, the transfer fractions of the internal organs relative to that of bone should be greater for subjects with high concentrations of skeletal Th than for those with low concentrations. However, a significant mass effect is not evident for liver; the first two subjects in Table 10 have skeletal concentrations more than 50 times larger than those of the last two, but the transfer fractions found for the latter are not much less than those of the

former. The higher spleen fractions of the Th workers compared to those of the non-occupational cases suggest a relationship to the characteristics of the aerosol inhaled during occupational exposure rather than to the amount inhaled. A possible mechanism would be the transfer of phagocytized particles from the lymph system to the spleen where particles of several micrometers diameter are preferentially retained (Robbins 1974). Stover et al. (1960, 1965) reported considerable damage and lower ^{228}Th retention in the kidneys of beagles in their high-level dose groups, but the radioactivity levels were much higher than those of the Th workers. Except for possible impairment of kidney function in the Th workers, however, it is difficult to interpret the apparently inverse relationship between Th concentrations and kidney transfer fractions that is seen for the subjects in Table 10. The same relationships between Th workers and the non-occupational cases were found for the fitted transfer fractions when T_{sk} was fixed at 8000 d and T_s of 2000 d to 16000 d were assumed for the other internal organs.

Fitted values of the respiratory-system parameters

Table 11 shows the fitted values that were obtained for parameters of the respiratory system in the same runs that provided the results of Table 10. Except for somewhat shorter half-times for lungs and lymph nodes, the general pattern of values for each case is similar to that obtained when the half-times of the body organs were allowed to vary. Significant changes from the ICRP30 parameter values for the pulmonary parenchyma and lymph nodes were required to fit the relative concentrations measured for lungs and lymph. The lung half-times (T_e) were about 1500 d for subjects L1521 and L2932, 1000 d for L0770 and L2107, and 500 d for the two non-occupational cases. For most of the subjects, the fraction of deposited Th going to the lymph nodes (F_h), the proportion held indefinitely (F_j), and the half-time (T_i) were less than half the values suggested by ICRP30 for Class Y aerosols in the lymph nodes. High values of both T_e and T_i were obtained for L1521, and the fraction held indefinitely by the lymph nodes (the product of F_h and F_j) was about the same as the ICRP30 value of 0.015.

Because eight parameters of the respiratory system could be varied, there was obviously much leeway in adjusting these parameters to reproduce the measured concentrations of Th in the lungs and lymph nodes relative to those of the internal body organs. However, differences in the fitted values of the respiratory values probably reflect actual differences in the aerosols inhaled by the individual subjects. Aerosols at the Th plant included monazite sands and compounds such as Th nitrate and Th oxides in various stages of drying and grinding, so job differences among the workers might well have involved exposure to the various kinds of aerosols in different proportions. Physical evidence of the inhalation of unusually insoluble Th aerosols by L1521 was obtained when more than 10% of the Th in lung samples from this subject was found in residues remaining after attempted dissolution of the samples, whereas lung and lymph samples from the other Th workers left much smaller residues that contained little or no Th (Stehney and Lucas 1991). In addition, large amounts of rare earths were found in the lungs of L1521*, so the matrix material in which Th was inhaled may have been qualitatively different from that of the other cases and/or the sheer mass of material may have impaired lung clearance. The respiratory parameters fitted to the data for L1521 (Table 11) are compatible with the physical findings, i.e., the fractions going directly to body fluids (F_c and F_e) were by far the smallest of any of the cases and the fraction retained in the lymph nodes was by far the largest.

Separate runs were made with T_e fixed at the same value for all of the subjects during the fitting procedure in order to test the possibility that the differences in T_e that had been found were calculation artifacts of the exposure times of the subjects instead of an indication of genuine differences in metabolism or in the nature of the aerosols to which the subjects had been exposed. As might be expected, there was little change from the values of Table 11 in the parameters for subjects R-M and G-J when the value of T_e was fixed at 500 d, for L0770 and L2107 at 1000 d, and for L1521 and L2932 at 1500

*Personal communication (1983) from R. E. Toohey, Argonne National Laboratory, Argonne, IL 60439.

d. The fitting routine obtained good fits for R-M and G-J with T_e at 1000 d and at 1500 d by increasing the fraction of Th quickly transferred from the lung to the GI tract and increasing the fraction to lymph nodes. For L0770 and L2107, the fractions of activity going directly to the body fluids and to the lymph nodes were reduced when T_e was held at 500 d and increased when T_e was held at 1500 d. Satisfactory fits could not be obtained for L1521 and L2932 when T_e was fixed at 500 d, and the fractions to the body fluids and to the lymph nodes had to be reduced to obtain good fits at 1000 d. The parameter values that were obtained for the respiratory system when T_e was held at 1500 d are shown in Table 12 for comparison with the values of Table 11. Evidently, it is quite possible to obtain good fits for all of the subjects with the same value of T_e but only with marked differences in the values of the other respiratory parameters.

In view of the fact that unique fits cannot be obtained when the number of adjustable parameters is greater than the number of values to be fitted, some tests were done to explore the range of parameters fitted to the data for each case under various conditions. When the initial values of the respiratory parameters were randomly chosen to be individually increased or decreased by a factor of two from the ICRP30 values previously used, the final value usually moved in the direction that the initial value of the parameter had been changed, but the general pattern of values between subjects was similar to that found previously. For two of the subjects, L0770 and L2932, satisfactory fits could not be obtained when the initial value of the half-time for lungs was reduced to 250 d.

The effect of possibly higher absorption of Th from the GI tract (Johnson and Lamothe 1989) was tested by the use of a fixed value of 0.01 instead of 0.0002 for f_1 . The only notable change from the parameter values of Tables 10 and 11 was a reduction of about 0.01 in the fitted values for the fractions going directly from the respiratory system to body fluids (F_c and F_e). Apparently, the fitting routine adjusted to the higher absorption of Th from the gut by merely reducing the absorption from the lungs and upper respiratory regions.

Attempts were also made to fit one set of parameters to the data for all the cases or subgroups of the cases. For these runs, it was assumed that the sum of the weighted squares of the differences between measured and calculated ratios had a chi-square distribution, and only the ratios to lung were used in order to limit the sum to values obtained only from independent ratios. Each subject provided a maximum of five independent ratios, but it was possible to have more data points than 11, the number of variable parameters, by combining cases. However, extremely poor fits (P less than 0.005) were obtained for the only logically grouped cases with more than zero degrees of freedom, namely, all the subjects (26 ratios) and the four Th workers (16 ratios). For combinations of three Th workers (12 ratios each), P less than 0.02 was obtained for the subgroup of L0770, L2107, and L2932, and less than 0.005 for the other three possible combinations. For the subgroup of two non-occupational cases combined, which had fewer ratios (10) than variable parameters, the sum of the chi-squares was 3.2 and the fitted values were mostly intermediate to the values obtained for the individual subjects.

Inhalation rates and dose equivalents

Although only the organ to organ ratios of Th concentrations were used when fitting parameters, the quantity actually calculated for each organ was the concentration per unit inhalation rate of Th activity. For each set of fitted parameters, estimates of the inhalation rate of a subject averaged over his exposure period could be obtained by dividing the measured concentration in each organ by the concentration calculated for that organ. All the organs provided essentially the same values of the inhalation rate for a given subject when a good fit was obtained to the measured body distribution of Th. These estimates and the values of the parameters were used to calculate the dose equivalents received by the organs.

The doses were calculated with the usual methodology of ICRP30 for radioactive decay chains, i.e., inhalation of only the parent ^{232}Th and subsequent growth of radioactive descendants that were assumed to have the metabolic properties of the parent. Dosimetric data for the ^{232}Th decay series and details of calculating dose equivalents are given in Appendix B.

In brief, the dose calculations consisted of calculating the numbers of transformations of each nuclide in each organ, in the body fluids, and in the GI tract, and multiplying by the specific effective energy appropriate to each combination of nuclide, source and target.

Table 13 displays the dose equivalents from the ^{232}Th radioactive decay chain that were calculated for each subject with the parameters and inhalation rates that were fitted to the concentrations of ^{232}Th measured in autopsy samples from his body. The average ^{232}Th inhalation rates calculated for each subject are shown in the fourth column of the table.

It may be noted that average inhalation rates of about 100 Bq y^{-1} were obtained for the plant electrician and the two Th workers directly involved in the production of Th materials. Dividing these rates by $2400 \text{ m}^3 \text{ y}^{-1}$, the occupational breathing rate for Reference Man (ICRP 1975, ICRP 1979a), leads to an estimate of about 0.04 Bq m^{-3} for the time-weighted average concentration of ^{232}Th in air inhaled by these men during work periods. This concentration is at the low end of the values of 0.05 to 5 Bq m^{-3} that have been reported for the plant (Albert et al. 1955, Mausner 1982), but it seems like a reasonable representation of actual exposure levels in various parts of the plant and in periods of low as well as high Th production. Comparison may be made with occupational standards for radioprotection: the Nuclear Regulatory Commission's maximum permissible concentration of ^{232}Th (USNRC 1986) is equivalent to 1.1 Bq m^{-3} ($3 \times 10^{-11} \text{ } \mu\text{Ci ml}^{-1}$), and the derived air concentration (DAC) given in ICRP30 for class Y compounds of ^{232}Th is 0.04 Bq m^{-3} , which is remarkably close to the average concentrations found for the Th workers. Like the Th inhalation rates, the dose equivalents calculated for the Th workers are close to limits recommended by the ICRP for occupational exposure to radiation. The annual dose-commitment system of the ICRP (ICRP 1977) for limiting intake of radioactivity is based on limits of 0.5 Sv y^{-1} (50 rem y^{-1}) for non-stochastic risk to single organs and 0.05 Sv y^{-1} effective dose equivalent (H_E) for stochastic risks. For L1521, the Th worker with the largest dose to the lungs (Table 13), the dose equivalent calculated for lungs was 9.3 Sv and the H_E was 1.1 Sv , so the average dose rates over the 25 years from the start of his last major exposure period to death (Table 3)

were about 0.4 Sv y^{-1} for lungs and 0.04 Sv y^{-1} for H_E . Presumably, inhalation of ^{228}Th as the parent of radionuclides further down the decay chain would add to the radiation doses, because ordinary Th aerosols have $^{228}\text{Th}/^{232}\text{Th}$ activity ratios of about 0.4 to 1.0 (Rundo 1978).

The annual breathing rate for male workers not occupationally exposed to Th may be taken to be 8000 m^3 (2400 m^3 during working hours and 5600 m^3 at other times). On this basis, the inhalation rate of 0.04 Bq y^{-1} ^{232}Th that was obtained for the composite non-occupational group in Table 13 (G-J) corresponds to an average concentration of $5 \text{ } \mu\text{Bq m}^{-3}$ in air inhaled at Grand Junction, Colorado. This is somewhat higher than the concentrations of $1.4 \text{ } \mu\text{Bq m}^{-3}$ in air of New York city at 14 floors above street level in 1979 (Wrenn et al. 1981) and 0.3 to $0.6 \text{ } \mu\text{Bq m}^{-3}$ at Argonne National Laboratory in 1975 (Golchert et al. 1976). The H_E s of about 1 mSv (100 mrem) calculated for lifetime Th exposures of the two non-occupational cases imply dose rates that are considerably less than the annual limit of 0.25 mSv (25 mrem) to the whole body set by the U.S. Environmental Protection Agency for exposure to the public from nuclear energy operations (USEPA 1977).

The annual limit on intake (ALI) and the corresponding derived air concentration (DAC) for each set of parameters are shown in Table 14 for the radioactive decay chains headed by ^{232}Th and by ^{228}Th . The values calculated in the present work from the ICRP30 compartmental model for Class Y aerosols with an AMAD of $1 \mu\text{m}$ agree well with those from ICRP30, which are given to only one significant figure. With few exceptions, the ALI values obtained with the parameter values fitted to the individual subjects are within a factor of two of those obtained with the original values from ICRP30. The non-stochastic risk to bone surfaces predominated in determining the ALIs for ^{232}Th , and the stochastic risk determined the ALIs for ^{228}Th for all the metabolic models. The very long retention times of Th in the respiratory system of L1521 and L2932 resulted in large calculated doses to the lungs which in turn made the H_E value large enough to be the determinant of the ALI for ^{232}Th for the metabolic models based on those two subjects. Compatibility between ICRP30's DAC for ^{232}Th and the dose equivalents calculated for the Th workers was indicated above in comments on the doses estimated for L1521.

Results obtained with the assumption of 50% transfer to muscle

Another set of calculations was made with fractional transfers of 0.2 and 0.5 of Th from body fluids to the skeleton and skeletal muscle, respectively, for comparison with results described above that were obtained with the ICRP30 value of 0.7 for F_{sk} . As before, T_{sk} was fixed at 8000 d. The starting values for the fitting procedure were also the same as before, except that F_{sk} was 0.2, and the transfer fractions for the other internal organs were based on translocation of 0.2 of the activity in body fluids to a remainder mass of 37 kg instead of 65 kg.

When the retention half-times for liver, spleen, and kidneys were allowed to vary, the fitted values ranged from about 2000 to 8000 days instead of the larger values in Table 9 that were obtained when F_{sk} was fixed at 0.7. On this basis, retention half-times of 4000 days were assumed for the three organs in subsequent calculations, and the parameter values that were fitted to the individual cases with this assumption are displayed in Table 15. Of course, the fitting routine was required to fit the same ratios of measured Th concentrations that had been fitted before, and comparison with Tables 10 and 11 shows that the routine adjusted to the reduced value of F_{sk} mostly by reducing the fraction of aerosol deposited in the pulmonary region, increasing the fractions going directly to body fluids, and reducing the transfer fractions for the internal organs. The removal half-times for lungs and lymph nodes were changed very little. The net effect was to reduce the activity concentrations calculated for unit intake rate, which in turn led to higher estimates of intake rates than those in Table 13.

The radiation doses calculated with the new fitted values of the parameters (Table 16) differ very little from those of Table 13, because the changes tended to cancel each other in the calculation of dose equivalents. However, the new values resulted in higher values of the ALIs, as shown in Table 17, because the organ activities calculated for a single intake of unit activity were lower.

It is perhaps unnecessary to mention that, in the absence of measurements of ^{232}Th in muscle samples from subjects with known exposure histories, it was not possible to determine whether 0.2 was a better estimate

of F_{sk} for humans than 0.7 simply by allowing this parameter to vary during the fitting routine. All the parameters moved simultaneously from their initial values toward a better fit, and if their initial values led to calculated activities that were too high for bone relative to the other organs, the eventually fitted value of F_{sk} was less than the initial value. Conversely, a set of initial values that led to too low a value for bone resulted in an increase in the fitted value. In essence, both parameters had to be specified for bone in order to adjust the other parameters by comparison of the measured concentrations of Th in the other organs with the measured concentration of Th in bone.

SUMMARY AND CONCLUSIONS

Parameters of the ICRP30 dosimetric models for the deposition and metabolism of inhaled Th were fitted to the measured concentrations of ^{232}Th in autopsy samples from four former employees of a Th refinery and two cases of non-occupational exposure to Th. The concentrations of Th in samples from the Th workers were 10 to 1000 times higher than in samples from the other cases.

The concentrations of Th in liver, spleen, and kidneys relative to the concentration in bone were higher than calculated from ICRP30's metabolic models for Th and compatible with retention half-times of 8000 d for all four organs, instead of 8000 d for bone and 700 d for the other three organs. For equal half-times and $f_2' = 0.7$ for bone, the fitted values of f_2' for liver were close to the ICRP30 value of 0.04 for all but one of the subjects (mean and standard deviation of 0.031 ± 0.010 for all subjects). For spleen, the fitted values of f_2' were about 0.025 for the Th workers and 0.01 for the non-occupational cases; for kidneys, the values were about 0.001 for the former and 0.01 for the latter. The constancy of the liver fractions indicates that there was little or no mass effect on the deposition of Th in bone relative to deposition in the liver at concentrations as high as about 10 μg of Th per gram of bone surface. The values for spleen and kidneys may have

been affected by the nature of the aerosols inhaled by the subjects and/or impairment of organ function.

Whereas ICRP30 uses removal half-times of 500 d for Class Y aerosols deposited in the pulmonary region, fitted values of 900 to 1600 d were obtained for Th in the lungs of the Th workers and about 500 d for the non-occupational cases. Instead of the ICRP30 value of 1000 d, the half-times in pulmonary lymph nodes were about 500 d for five of the six subjects; for the other subject (a Th worker), the fitted values of the parameters indicated almost no transfer of Th out of the lymph nodes. The variability most probably reflects differences in the solubilities, sizes, and/or masses of aerosols inhaled by the individual subjects.

In order to calculate radiation doses, general equations were derived for the activity of members of radioactive decay chains in successive metabolic compartments as a function of exposure duration and time after the end of exposure. Inhalation rates calculated for individual Th workers ranged from 50 to 110 Bq ^{232}Th y^{-1} , and dose equivalents calculated from the inhalation rates and fitted values of the metabolic parameters were as high as 9.3 Sv to the lungs, 2.0 Sv to bone surfaces, and 1.1 Sv for H_2 . Despite some notable differences between the fitted values and the ICRP30 values for the metabolic parameters of Th, the ICRP30 annual limits on intake of 100 Bq for ^{232}Th and 600 Bq for ^{228}Th were found to be applicable to within a factor of about three over the range of values fitted to the subjects studied in this report.

When f_2' for bone was assumed to be 0.2 instead of the ICRP30 value of 0.7, the fitted parameters were qualitatively similar to those described above, and the calculated radiation doses to the subjects were about the same. It was not possible to determine a preferred value for f_2' from the data available.

The calculation methods described in this paper provide a systematic and objective procedure for including time relationships when comparing concentrations of radioactivity measured in autopsy samples with concentrations calculated from metabolic models. One can obtain retrospective estimates of radiation doses to individuals who may have inhaled long-lived

radionuclides that were not measured in vivo, and the methods could be extended to calculate the time accumulation of radiation dose for risk estimates.

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For purposes of radiological protection, ICRP usually assumes that the members of a radioactive decay chain have the metabolic properties of the first member of the chain that enters the body. The same assumption is used below in deriving equations for the activities of the daughter products.

Activities after a single deposition

The rate of change of the number of atoms of any species in any compartment is the rate of entry from the previous compartment plus the rate of production from atoms of the parent within the compartment plus the rate of entry from outside the system less the total loss rate of atoms of the species in the compartment. If there is no entry from outside the system, the corresponding differential equation is

$$\frac{dN_i^j}{dt}(t) = \lambda_{(i-1,i)} N_{i-1}^j(t) + \mu_{(j-1,j)} N_i^{j-1}(t) - (\lambda_i + \mu_j) N_i^j(t) ,$$

where: N_i^j is the number of atoms of the j^{th} member of the decay chain in the i^{th} compartment; $\lambda_{(i-1,i)}$ is the rate constant for transfer from compartment $i-1$ to compartment i ; $\mu_{(j-1,j)}$ is the rate constant for transformation from species $j-1$ to species j ; and λ_i and μ_j are rate constants for loss from transfer out of the compartment and from radioactive decay, respectively. The equation for activity is obtained by multiplying the numbers of atoms by the radioactive decay constant of the j^{th} member, i.e.,

$$\frac{dq_i^j}{dt}(t) = \lambda_{(i-1,i)} q_{i-1}^j(t) + \mu_{(j-1,j)} \frac{\mu_j}{\mu_{j-1}} q_i^{j-1}(t) - (\lambda_i + \mu_j) q_i^j(t) . \quad (\text{A.1})$$

For a single instantaneous injection of quantity $q_1^1(0)$ of the first member of the radioactivity chain into the first compartment at time $t=0$ and no other entry from outside the system, ICRP30 (p. 56) gives the solutions for $j=1$ as

$$q_i^1(t) = \left[\prod_{k=1}^{i-1} \lambda_{(k,k+1)} \right] \sum_{k=1}^i \left\{ \frac{q_1^1(0) e^{-(\lambda_k + \mu_1)t}}{\prod_{p=1, p \neq k}^i [(\lambda_p + \mu_1) - (\lambda_k + \mu_1)]} \right\} , \quad (\text{A.2})$$

and the solutions for $i=1$ are given by the Bateman equations for a radioactive decay series (Evans 1955) as

$$Q_1^j(t) = \frac{\mu_j}{\mu_1} \left[\prod_{m=1}^{j-1} \mu_{(m,m+1)} \right] \sum_{m=1}^j \left\{ \frac{Q_1^1(0) e^{-(\lambda_1 + \mu_m)t}}{\prod_{r=1, r \neq m}^j [(\lambda_1 + \mu_r) - (\lambda_1 + \mu_m)]} \right\}, \quad (\text{A.3})$$

where Σ and Π are the sum and product, respectively, of the indicated quantities, and $\Pi=1$ when $i=1$ or $j=1$.

Solutions for other values of i and j can be derived in steps by substituting into eqn (A.1) the solutions obtained for species j in compartment $i-1$ and for species $j-1$ in compartment i . For example, for the second species in the second compartment,

$$\frac{dQ_2^2}{dt}(t) = \lambda_{(1,2)} Q_1^2(t) + \mu_{(1,2)} \frac{\mu_2}{\mu_1} Q_2^1(t) - (\lambda_2 + \mu_2) Q_2^2(t) .$$

From eqn (A.2)

$$Q_2^1(t) = Q_1^1(0) \lambda_{(1,2)} \left[\frac{e^{-(\lambda_1 + \mu_1)t}}{(\lambda_2 + \mu_1) - (\lambda_1 + \mu_1)} + \frac{e^{-(\lambda_2 + \mu_1)t}}{(\lambda_1 + \mu_1) - (\lambda_2 + \mu_1)} \right] ,$$

and from eqn (A.3)

$$Q_1^2(t) = Q_1^1(0) \mu_{(1,2)} \frac{\mu_2}{\mu_1} \left[\frac{e^{-(\lambda_1 + \mu_1)t}}{(\lambda_1 + \mu_2) - (\lambda_1 + \mu_1)} + \frac{e^{-(\lambda_1 + \mu_2)t}}{(\lambda_1 + \mu_1) - (\lambda_1 + \mu_2)} \right] .$$

The solution for $Q_2^2(t)$ can then be obtained as

$$q_2^2(t) = q_1^1(0) \lambda_{(1,2)} \mu_{(1,2)} \frac{\mu_2}{\mu_1} \left[\frac{e^{-(\lambda_1+\mu_1)t}}{(\lambda_2-\lambda_1)(\mu_2-\mu_1)} + \frac{e^{-(\lambda_2+\mu_1)t}}{(\lambda_1-\lambda_2)(\mu_2-\mu_1)} + \frac{e^{-(\lambda_1+\mu_2)t}}{(\lambda_2-\lambda_1)(\mu_1-\mu_2)} + \frac{e^{-(\lambda_2+\mu_2)t}}{(\lambda_1-\lambda_2)(\mu_1-\mu_2)} \right] .$$

The general solution obtained for the activity of the j^{th} species in the i^{th} compartment after a single instantaneous deposition of the first species in the first compartment may be expressed in condensed form as

$$q_i^j(t) = q_1^1(0) \left[\prod_{k=1}^{i-1} \lambda_{(k,k+1)} \right] \left[\frac{\mu_j}{\mu_1} \prod_{m=1}^{j-1} \mu_{(m,m+1)} \right] \times \sum_{k=1}^i \left| \sum_{m=1}^j \left\{ \frac{e^{-(\lambda_k+\mu_m)t}}{\left[\prod_{p=1, p \neq k}^i (\lambda_p - \lambda_k) \right] \left[\prod_{r=1, r \neq m}^j (\mu_r - \mu_m) \right]} \right\} \right| . \quad (\text{A.4})$$

Continuous deposition of the parent activity

For continuous deposition of the parent activity at unit rate, the increment of activity of the j^{th} species in the i^{th} compartment at time $T-t$ after a short intake period, dt , that occurs at time t after the start of intake will be the same as the amount resulting from an instantaneous deposition of parent activity numerically equal to dt . Then from eqn (A.4)

$$dq_i^j(T) = C_1^j \langle e^{-(\lambda_k+\mu_m)(T-t)} dt \rangle , \quad (\text{A.5})$$

where T is the time after start of intake and

$$C_i^j \langle \rangle = \left[\prod_{k=1}^{i-1} \lambda_{(k, k+1)} \right] \left[\frac{\mu_j}{\mu_1} \prod_{m=1}^{j-1} \mu_{(m, m+1)} \right]$$

$$\times \sum_{k=1}^i \left| \sum_{m=1}^j \left\{ \frac{\langle \rangle}{\left[\prod_{p=1, p \neq k}^i (\lambda_p - \lambda_k) \right] \left[\prod_{r=1, r \neq m}^j (\mu_r - \mu_m) \right]} \right\} \right|$$

is an operator acting on the function within the angle brackets. In eqn A.5, the function is $\exp[-(\lambda_k + \mu_m)(T-t)]dt$.

Integration of eqn (A.5) between time zero and time T provides the following expression for the activities at time T during continuous intake of duration T_1 at unit rate:

$$q_i^j(T \leq T_1) = C_i^j \left\langle \frac{[1 - e^{-(\lambda_k + \mu_m)T}]}{(\lambda_k + \mu_m)} \right\rangle ; \quad (A.6)$$

and integration between time zero and time T_1 provides the following expression for the activities after intake has ceased:

$$q_i^j(T > T_1) = C_i^j \left\langle \frac{[e^{(\lambda_k + \mu_m)T_1} - 1] e^{-(\lambda_k + \mu_m)T}}{(\lambda_k + \mu_m)} \right\rangle . \quad (A.7)$$

Numbers of transformations

The number of transformations of each species in each compartment during intake at unit rate is the time integral of eqn (A.6) from zero to the end of intake, i.e.,

$$U_i^j(0, T_1) = C_i^j \left\langle \frac{T_1}{(\lambda_k + \mu_m)} - \frac{[1 - e^{-(\lambda_k + \mu_m)T_1}]}{(\lambda_k + \mu_m)^2} \right\rangle ,$$

and the number of transformations after the end of intake is the time integral of eqn (A.7) from time T_1 to T , i.e.,

$$U_i^j(T_1, T) = C_i^j \left\langle \frac{[e^{(\lambda_k + \mu_m) T_1} - 1] [e^{-(\lambda_k + \mu_m) T_1} - e^{-(\lambda_k + \mu_m) T}]}{(\lambda_k + \mu_m)^2} \right\rangle .$$

The total number of transformations is the sum of the two integrations:

$$U_i^j(0, T) = C_i^j \left\langle \frac{T_1}{(\lambda_k + \mu_m)} - \frac{[e^{(\lambda_k + \mu_m) T_1} - 1] e^{-(\lambda_k + \mu_m) T}}{(\lambda_k + \mu_m)^2} \right\rangle .$$

Finally, the total numbers of transformations of each species in each compartment from time zero to time T may also be expressed as the numbers from time zero to time $(T_1 + T_2)$, where T_2 is the time after the end of an intake period of duration T_1 at unit intake rate:

$$U_i^j(0, T_1 + T_2) = C_i^j \left\langle \frac{T_1}{(\lambda_k + \mu_m)} - \frac{[1 - e^{-(\lambda_k + \mu_m) T_1}] e^{-(\lambda_k + \mu_m) T_2}}{(\lambda_k + \mu_m)^2} \right\rangle . \quad (A.8)$$

APPENDIX B. DOSE EQUIVALENTS

The dose equations of ICRP30 (Chapter 4) and dosimetric data from the supplement to ICRP 30 (ICRP 1979b) and from Lederer et al. (1967) were used to calculate the dose equivalents, H, in target organs irradiated by radiations from Th and Th decay-products in the body. From eqn (4.7) of ICRP30, the value of H in target T is given by

$$H_T = 1.6 \times 10^{-10} \sum_S \sum_j [U_S^j \text{SEE}(T \sim S)_j] \text{ Sv},$$

where: 1.6×10^{-10} is a factor to convert from MeV g⁻¹ to J kg⁻¹; the summation in S is over all sources irradiating the target organ; the summation in j is over all radionuclides in source S; U_S^j is the number of transformations of the jth radionuclide in S; and $\text{SEE}(T \sim S)_j$ is the specific effective energy absorbed in target T from transformations of radionuclide j in S.

From eqn (4.8) of ICRP30,

$$\text{SEE}(T \sim S)_j = \frac{\sum_i Y_i E_i \text{AF}(T \sim S)_i Q_i}{M_T} \text{ MeV g}^{-1} \text{ tr}^{-1},$$

where: the summation in i is over all radiation types i produced in yield Y_i with energy E_i (MeV) per transformation of radionuclide j in source S; $\text{AF}(T \sim S)_i$ is the fraction of energy of radiation type i absorbed in target organ T; Q_i is the quality factor for radiation of type i; and M_T is the mass (g) of the target organ.

Dosimetric data

Table B.1 gives a summary of the radiations emitted by ²³²Th and daughter products in type classifications suitable for the internal dosimetry of these radionuclides: alpha particles, beta particles with mean energies less than 0.2 MeV, beta particles with mean energies greater than or equal to 0.2 MeV, and gamma rays with yields of 0.001 or more per transformation. The

values shown for α , β_1 , β_2 , and γ , respectively, are Y_i times E_i summed over i for each radiation class.

Quality factors of 20 for alpha particles, one for beta particles, and one for gamma rays were used. Except for bone, it was assumed that alpha particles and beta particles were completely absorbed in the organs in which they were produced; for these organs the SEE values were obtained from the relationship

$$SEE(S \leftarrow S)_j = \frac{(\alpha + \beta_1 + \beta_2)_j}{M_S} \text{ MeV g}^{-1} \text{ tr}^{-1}.$$

For bone surfaces and red marrow as target organs, the absorbed fractions (AF) used were those given in Chapter 7 of ICRP30 for radionuclides on the surfaces of trabecular bone and on the surfaces of cortical bone; restated for the activity on all bone surfaces, the relationships for SEE are

$$SEE(BS \leftarrow BONE)_j = \frac{(0.25 \alpha + 0.25 \beta_1 + 0.02 \beta_2)_j}{M_{BS}} \text{ MeV g}^{-1} \text{ tr}^{-1}$$

for bone surfaces as the target, and

$$SEE(RM \leftarrow BONE)_j = \frac{(0.25 \alpha + 0.25 \beta_1 + 0.25 \beta_2)_j}{M_{RM}} \text{ MeV g}^{-1} \text{ tr}^{-1}$$

for red marrow as the target.

Since alpha particles are by far the largest contributors to the radiation dose from internally-deposited Th and daughters, it was possible to make the simplifying assumption for electromagnetic radiation that all the radionuclides in the body were uniformly distributed throughout the body as the source of gamma rays and with the total body (TB) as the target. The calculation was further simplified by the fact that the Specific Absorbed Fraction ($\Delta E/E^0 \text{ g}^{-1}$) for (TB $\leftarrow$ TB) is almost constant at about $5 \times 10^{-6} \text{ g}^{-1}$ for photons with energies of about 0.1 MeV or more (ICRP 1975, Appendix I). For gamma rays, the following relationship could then be used:

$$SEE(TB \leftarrow TB)_j = 5 \times 10^{-6} \gamma_j \text{ MeV g}^{-1} \text{ tr}^{-1}.$$

Sources and target organs

Source organs and target organs for calculation of dose equivalents are listed in Table B.2, together with target masses of Reference Man (ICRP 1979a) and the weighting factors (W_T) recommended by the ICRP for stochastic risks (ICRP 1977). Also shown are the values of $SEE(T \rightarrow S)$ for ^{232}Th ; ^{228}Ra and its short-lived daughter, ^{228}Ac ; ^{228}Th ; and ^{224}Ra and its short-lived daughter products. These values were obtained from the dosimetric data in Table B.1 and the equations given above. The source masses are the same as the target masses except for bone, which is 5000 grams of mineralized skeleton without marrow and other associated material (ICRP 1975). As suggested by the ICRP (ICRP 1977), the lung was considered to be a 1000-gram composite of the tracheobronchial region, pulmonary region, and the pulmonary lymph nodes, and radioactive transformations in the three regions were summed to obtain the number of transformations in lungs as a source. Transformations that occurred in the transfer compartment (body fluids) were added to the number calculated for the organs in proportion to the ratio of the organ masses to the total body mass of 70000 g. For the total body as a source of gamma rays, transformations in the gastrointestinal tract were added to the total number of transformations that occurred within the body; for this purpose, the number of transformations in the entire GI tract was estimated by calculating the number in the small intestine and multiplying by 10, the ratio of the sum of the mean residence times in the GI compartments to the mean residence time in the small intestine.

TABLE CAPTIONS

- Table 1. ICRP30 model for deposition and clearance of class Y, 1μ AMAD aerosols in the respiratory system.
- Table 2. ICRP30 models for transfer and clearance of Th in body systems.
- Table 3. Case histories of exposure to Th.
- Table 4. Measured concentrations of Th in autopsy samples ($\text{mBq } ^{232}\text{Th g}^{-1}$): geometric mean and geometric standard error (GSE) of N samples of each type of tissue.^{a,b}
- Table 5. Adjusted concentrations of Th in autopsy samples ($\text{mBq } ^{232}\text{Th g}^{-1}$): geometric means and geometric standard errors (GSE) of N samples of each tissue.^{a,b}
- Table 6. Organ and tissue masses of Reference Man.^a
- Table 7. Working model for deposition and clearance of aerosols in the respiratory system.^a
- Table 8. Ratios of concentrations of Th in organs to concentration in bone: comparison of measured ratios with ratios calculated from parameter values in ICRP30 for Class Y, $1\mu\text{m}$ aerosols.
- Table 9. Fitted values obtained for the transfer fractions and retention half-times (d) of internal organs^a relative to $F_{\text{sk}}=0.7$ and $T_{\text{sk}}=8000$ d.
- Table 10. Skeletal concentrations of ^{232}Th vs. transfer fractions fitted to the internal organs when the transfer fraction for bone was fixed at 0.7 and the retention half-times of all internal organs were fixed at 8000 d.
- Table 11. Parameter values fitted to the metabolic model for the respiratory system^a when the transfer fraction for bone was fixed at 0.7 and the retention half-times of all internal organs were fixed at 8000 d.
- Table 12. Parameter values fitted to the metabolic model for the respiratory system^a when T_e was held at 1500 d and all other conditions were the same as those described for Table 11.
- Table 13. Dose equivalents from ^{232}Th + daughters calculated from parameter values and inhalation rates fitted to individual cases.^a

Table 14. Annual limits on intake (ALIs) calculated from parameter values fitted to individual cases as metabolic models (from Tables 10 and 11).

Table 15. Parameter values^a fitted to the metabolic models for Th when the fractions of Th transferred from body fluids were fixed at 0.2 to the skeleton and 0.5 to skeletal muscle.^b

Table 16. Dose equivalents from ^{232}Th + daughters calculated from parameters and inhalation rates fitted to individual cases with the transfer fraction for bone fixed at 0.2.^a

Table 17. Annual limits on intake (ALIs) calculated from parameter values fitted to individual cases when the transfer fraction for bone was fixed at 0.2.

Table B.1. Dosimetric data for ^{232}Th decay series.

Table B.2. Source and target organs and specific effective energies for the ^{232}Th decay series.

Region ^a	Deposition ^b		Clearance ^c	
	Compartment	Fraction	Half-time (d)	Path
Nasopharyngeal ($D_{NP}=0.30$)	a	0.01	0.01	Body fluids
	b	0.99	0.40	GI tract
Tracheobronchial ($D_{TB}=0.08$)	c	0.01	0.01	Body fluids
	d	0.99	0.20	GI tract
Pulmonary ($D_P=0.25$)	e	0.05	500	Body fluids
	f	0.4	1.0	Compartment d
	g	0.4	500	Compartment d
	h	0.15	500	Lymph nodes
L ^d	i	0.9	1000	Body fluids
	j	0.1	∞	----

^a D_{NP} , D_{TB} , and D_P : fractions of the inhaled aerosol deposited in the nasopharyngeal, tracheobronchial (TB), and pulmonary (P) regions, respectively.

^b F_a , F_b , etc. are compartmental fractions of regional deposition.

^c T_a , T_b , T_c , etc. are compartmental removal half-times.

^dPulmonary lymphatic system; i and j are compartments in the pulmonary lymph nodes (PLN).

System	Transfer ^a		Clearance ^b	
	Compartment	Fraction	Half-time (d)	Path
GI Tract	Stomach	1.00	0.029	Small intestine
	Small int.	1.00	0.116	Body fluids (0.02%)
				Large intestine
Body Fluids	Transfer	----	0.5	Organs (90%) Excreta
Int. Organs	Skeleton	0.70	8000	Excreta
	Liver	0.04	700	Excreta
	Spleen	(Other)	(Other)	----
	Kidneys	(Other)	(Other)	----
	Other	0.16	700	Excreta

^aThe fractions transferred from body fluids to organs and tissues (f_2') are designated in this paper as F_{Sk} , F_{Lv} , F_{Sp} , and F_{Kd} for bone, liver, spleen, and kidneys, respectively.

^bThe retention half-times in organs and tissues (biological half-lives) are designated as T_{Sk} , T_{Lv} , T_{Sp} , and T_{Kd} for bone, liver, spleen and kidneys, respectively.

A. Th Workers

Subject	Sex	Job	Job Dates	Years On Job	Years to Death After Job	Age At Death
L0770	M	Millwright Electrician	1948 1959-1966	0.2 6.6	33.5 15.5	63
L1521	M	Laborer Rare-Earth Prod'n	1950-1958 1958-1973	7.7 15.2	24.9 9.7	63
L2107	M	Laborer Fireman Th Production	1938-1942 1945-1947 1954-1973	3.0 1.9 18.9	37.1 31.5 5.6	58
L2932	M	Laborer Truck Driver	1941 1943-1945	0.6 2.5	35.0 30.8	72

B. Non-occupational^a

Subject	Sex	Occupation	Age At Death
R-M	M	Hard Rock Miner	72
G-J ^b	M	Various	70

^aFrom Wrenn et al. (1981).

^bComposite of five subjects (mean age 70 at death).

Subject	Lungs	PLN ^c	Bone	Liver	Spleen	Kidneys
L0770	1.75	5.40	0.70	0.17	0.97	na ^d
GSE (N)	1.10 (2)	(0.26)	1.27 (4)	(0.01)	(0.03)	
L1521	67.1	1210.	0.58	0.15	1.08	na
GSE (N)	1.19 (3)	(40.)	1.17 (4)	1.14 (2)	1.06 (2)	
L2107	12.1	30.7	na	0.68	5.25	0.068
GSE (N)	1.29 (9)	2.00 (2)		(0.03)	1.10 (2)	(0.004)
I-2932	0.24	3.86	0.16	0.015	na	0.009
GSE (N)	1.45 (2)	(0.20)	1.07 (2)	(0.003)		(0.002)
R-M	0.023	0.17	0.012	0.0022	0.0044	0.0041
GSE (N=1)	(0.007)	(0.05)	(0.003)	(0.0007)	(0.0015)	(0.0015)
G-J	0.0074	0.21	0.0042	0.0009	0.0024	0.0015
GSE (N)	1.72 (5)	1.31 (5)	1.47 (5)	1.34 (5)	1.54 (5)	1.87 (5)
Normals ^e	0.0125	0.22	0.0039	0.0015	0.0026	0.0018
GSE (N)	1.22 (20)	1.15 (17)	1.23 (15)	1.28 (18)	1.27 (11)	1.26 (18)

^aData for thorium workers from Stehney and Lucas (1990);
data for others from Wrenn et al. (1981).

^bIf only one sample was measured, the standard error (SE) of the measurement is shown in parentheses below the measured value.

^cPLN = pulmonary lymph nodes.

^dna = not available.

^eGeometric means of measurements of samples from all men in two general populations (from Wrenn et al. 1981).

Subject	Lungs	PLN	Bone	Liver	Spleen	Kidneys
L0770	1.74	5.40	0.70	0.17	0.96	na
GSE (N)	1.10 (2)	1.29 (1)	1.28 (4)	1.28 (1)	1.28 (1)	
L1521	67.1	1210.	0.58	0.15	1.07	na
GSE (N)	1.1 ^a (3)	1.29 (1)	1.18 (4)	1.15 (2)	1.06 (2)	
L2107	12.1	30.5	na	0.68	5.25	0.066
GSE (N)	1.29 (9)	2.01 (2)		1.28 (1)	1.11 (2)	1.28 (1)
L2932	0.23	3.64	0.15	0.013	na	0.007
GSE (N)	1.53 (2)	1.29 (1)	1.10 (2)	1.39 (1)		1.63 (1)
R-M	0.023	0.17	0.012	0.0022	0.0044	0.0041
GSE (N=1)	1.42	1.44	1.28	1.50	1.50	1.57
G-J	0.0074	0.21	0.0042	0.00087	0.0024	0.0015
GSE (N)	1.72 (5)	1.31 (5)	1.47 (5)	1.34 (5)	1.54 (5)	1.87 (5)

^aThe concentrations shown for the former Th workers are net after subtraction of the values for "Normals" (Table 4) as an adjustment for environmental levels; no subtraction was made for subjects R-M and G-J.

^bIf only one sample was measured, the GSE shown was estimated from the standard error of the measurement or set equal to the GSE of lung samples of L2107 or bone samples of L0770, as described in Materials.

Organ or Tissue	Mass (g)
Total body	70000
Trachea-Bronchi	40
Pulmonary parenchyma	945
Pulmonary lymph nodes	15
Skeleton	10000
wet, fat-free	8000
mineralized bone	5000
Liver	1800
Spleen	180
Kidneys	310
Skeletal muscle	28000

^aFrom ICRP 1975 and ICRP 1979a

Region	Deposition		Clearance	
	Compartment	Fraction	Half-time (d)	Path
Nasopharyngeal ($D_{NP}=0.80-0.08-D_p$)	a	F_c	0.01	Body fluids
	b	$1-F_c$	0.40	GI tract
Tracheobronchial ($D_{TB}=0.08$)	c	F_c	0.01	Body fluids
	d	$1-F_c$	0.20	GI tract
Pulmonary (D_p)	e	F_e	T_e	Body fluids
	f	$1-F_e-F_g-F_h$	1.0	Compartment d
	g	F_g	T_e	Compartment d
	h	F_h	T_e	Lymph nodes
Pulmonary lymph nodes	i	$1-F_j$	T_1	Body fluids
	j	F_j	∞	----

^aVariable parameter values are D_p and the five F s and two T s shown as symbols. The symbols are defined in the footnotes of Table 1.

Subject	Measured(organ/bone) / Calculated(organ/bone)				
	Lungs	PLN	Liver	Spleen	Kidneys
L0770	330.	0.072	25.	1270.	na
GSE ^a	1.30	1.43	1.42	1.42	--
L1521	2870.	17.	19.	1220.	na
GSE	1.26	1.35	1.24	1.19	--
L2932	23600.	0.17	176.	na	770.
GSE	1.55	1.31	1.40	--	1.64
R-M	0.74	0.066	7.4	130.	120.
GSE	1.53	1.55	1.61	1.61	1.67
G-J	0.68	0.23	8.1	190.	120.
GSE	1.94	1.60	1.62	1.78	2.09
L2107 ^b	---	0.0049	0.62	42.	0.54
GSE	---	2.11	1.43	1.32	1.43

^aGeometric standard errors of the measured ratios.

^bRatios of concentrations in organs to concentration in lungs.

Subject	(1) Individual half-times						(2) One half-time in common			
	T _{Lv}	F _{Lv}	T _{Sp}	F _{Sp}	T _{Kd}	F _{Kd}	T	F _{Lv}	F _{Sp}	F _{Kd}
L0770	5600	0.046	27600	0.016	na	na	24500	0.027	0.016	na
L1521	7300	0.041	39800	0.023	na	na	59300	0.031	0.023	na
L2107 ^b	(8000)	(0.04)	34000	0.022	1700	0.002	(8000)	(0.04)	0.030	0.001
L2932	3800	0.031	na	na	2900	0.004	3700	0.033	na	0.003
R-M	5300	0.041	7500	0.006	7400	0.010	7700	0.031	0.006	0.010
G-J	5500	0.044	9600	0.008	7300	0.010	10700	0.027	0.007	0.008

^aSymbols for internal organs are defined in the footnotes of Table 2.

^bFor L2107, the fitted values for spleen and kidneys were obtained relative to fixed values of F=0.04 and T=8000 d for liver.

Subject	Skeletal Th ^a		Transfer fraction		
	mBq g ⁻¹	µg g ⁻¹	Liver	Spleen	Kidneys
L0770	0.70	11.5	0.037	0.022	na
L1521	0.58	9.5	0.040	0.030	na
L2107	na	na	(0.031)	0.023	0.0005
L2932	0.16	2.6	0.014	na	0.0012
R-M	0.012	0.20	0.030	0.006	0.0094
G-J	0.0042	0.07	0.034	0.009	0.0096

^aThe concentrations of Th are shown as mBq per gram of wet sample and as µg per gram of bone surface of 10 µm thickness.

Subject	D _p	F _c	T _e	F _e	F _g	F _h	T _i	F _j
L0770	0.15	0.019	1150	0.030	0.86	0.016	450	0.038
L1521	0.65	0.001	1550	0.003	0.86	0.019	3200	0.63
L2107	0.19	0.017	930	0.057	0.80	0.024	330	0.033
L2932	0.25	0.014	1620	0.040	0.80	0.035	570	0.038
R-M	0.13	0.025	530	0.14	0.48	0.049	310	0.033
G-J	0.17	0.018	420	0.098	0.41	0.080	510	0.053

^aSymbols are defined in the footnotes of Table 1.

Subject	D _p	F _c	T _e	F _e	F _g	F _h	T _i	F _j
L0770	0.13	0.022	(1500)	0.13	0.62	0.040	320	0.032
L1521	0.61	0.001	(1500)	0.003	0.86	0.017	4730	0.60
L2107	0.33	0.010	(1500)	0.26	0.49	0.087	240	0.021
L2932	0.32	0.010	(1500)	0.033	0.84	0.024	200	0.039
R-M	0.10	0.033	(1500)	0.17	0.11	0.061	410	0.038
G-J	0.09	0.036	(1500)	0.078	0.13	0.11	870	0.074

*Symbols are defined in the footnotes of Table 1.

Subject	Half-Time		Inhal. Rate (Bq y ⁻¹)	Dose Equivalent (mSv)						
	Lungs (d)	PLN (d)		Lungs	BS ^b	RM ^c	Lvr	Spln	Kdny	H _E ^d
L0770	1150	450	110.	470.	520.	41.	7.3	43.	1.0	80.
L1521	1550	3200	90.	9330.	370.	30.	5.7	42.	0.7	1140.
L2107	930	330	90.	1130.	1970.	160.	23.	170.	2.2	230.
L2932	1620	570	50.	310.	280.	22.	1.5	26.	0.7	40.
R-M	530	310	0.12	1.2	23.	1.8	0.3	0.5	0.5	1.1
G-J	420	510	0.04	0.5	7.8	0.6	0.1	0.3	0.2	0.4

^aParameter values from Tables 10 and 11.

^bBS = Bone surfaces.

^cBM = Active red bone marrow in trabecular bone.

^dEffective dose equivalent.

Chain	Model	Organ ^a	Non-stochastic risk			Stochastic risk		
			Dose (mSv)	ALI (Bq y ⁻¹)	DAC ^{b, c} (Bq m ⁻³)	H _E (mSv)	ALI (Bq y ⁻¹)	DAC (Bq m ⁻³)
²³² Th+d	ICRP30 ^d	BS		100	0.04		200	
	ICRP30 ^e	BS	5.0	100	0.042	0.31	160	
	L0770	BS	1.8	280	0.12	0.17	290	
	L1521	Lungs	6.0	80		0.74	70	0.029
	L2107	BS	2.5	200	0.083	0.19	260	
	L2932	BS	2.6	190		0.36	140	0.058
	R-M	BS	3.9	130	0.054	0.19	260	
	G-J	BS	4.0	120	0.050	0.21	240	
²²⁸ Th+d	ICRP30 ^d						600	0.3
	ICRP30 ^e	Lungs	0.68	740		0.091	550	0.23
	L0770	Lungs	0.74	680		0.10	500	0.21
	L1521	Lungs	3.6	140		0.43	120	0.050
	L2107	Lungs	0.86	580		0.11	450	0.19
	L2932	Lungs	1.4	360		0.17	290	0.12
	R-M	BS	0.35	1430		0.056	890	0.37
	G-J	Lungs	0.37	1350		0.059	850	0.35

^aThe organ receiving the largest dose equivalent and the dose to that organ are shown.

^bDAC = derived air concentration.

^cThe value of DAC is shown after the lower of the two values of ALI.

^dValues from ICRP 1979a.

^eValues calculated in this work for Class Y aerosols with an AMAD of 1µm.

Subj.	D _p	F _c	T _e	F _e	F _g	F _h	T _i	F _j	F _{Lv}	F _{Sp}	F _{Kd}
L0770	0.10	0.031	1080	0.123	0.75	0.018	320	0.027	0.018	0.011	na
L1521	0.67	0.000	1450	0.003	0.86	0.030	2380	0.22	0.017	0.012	na
L2107	0.11	0.028	800	0.092	0.76	0.023	240	0.026	(0.016)	0.012	0.0003
L2932	0.10	0.032	1560	0.080	0.79	0.030	610	0.038	0.010	na	0.0009
R-M	0.08	0.040	370	0.21	0.27	0.037	240	0.024	0.016	0.003	0.0050
G-J	0.11	0.028	250	0.15	0.22	0.053	340	0.035	0.017	0.005	0.0051

^aSymbols are defined in the footnotes of Tables 1 and 2.

^bRetention half-times fixed at 8000 d for the skeleton and 4000 d for the other internal organs.

Subject	Half-Time		Inhal. Rate (Bq y ⁻¹)	Dose Equivalent (mSv)						
	Lungs (d)	PLN (d)		Lungs	BS ^b	RM ^c	Lvr	Spln	Kdny	H _E ^d
L0770	1080	320	190.	530.	500.	40.	9.0	53.	1.7	93.
L1521	1450	2380	100.	10200.	350.	28.	6.0	44.	1.3	1240.
L2107	800	240	210.	1320.	1750.	140.	25.	190.	2.8	260.
L2932	1560	610	150.	340.	300.	24.	2.5	29.	1.3	57.
R-M	370	240	0.33	1.0	22.	1.7	0.3	0.5	0.5	1.2
G-J	250	340	0.14	0.5	7.5	0.6	0.1	0.3	0.2	0.4

^aParameter values from Table 15.

Chain	Model	Organ ^a	Non-stochastic risk			Stochastic risk		
			Dose (mSv)	ALI (Bq y ⁻¹)	DAC ^{b,c} (Bq m ⁻³)	H _E (mSv)	ALI (Bq y ⁻¹)	DAC (Bq m ⁻³)
²³² Th+d	ICRP30 ^a	BS	1.4	360		0.17	290	0.12
	L0770	BS	0.99	510		0.10	500	0.21
	L1521	Lungs	5.4	90		0.68	70	0.029
	L2107	BS	0.89	560	0.23	0.082	610	
	L2932	Lungs	0.92	540		0.14	360	0.15
	R-M	BS	1.3	380	0.16	0.072	690	
	G-J	BS	1.1	450	0.19	0.064	780	
²²⁸ Th+d	ICRP30 ^a	Lungs	0.68	740		0.084	600	0.25
	L0770	Lungs	0.51	980		0.067	750	0.31
	L1521	Lungs	3.6	140		0.44	110	0.046
	L2107	Lungs	0.47	1060		0.062	810	0.34
	L2932	Lungs	0.55	910		0.071	700	0.29
	R-M	BS	0.14	3600		0.024	2100	0.87
	G-J	Lungs	0.12	4200		0.022	2300	0.96

^aValues calculated in this work with the transfer fraction for bone = 0.2 instead of 0.7 and all other parameter values for Th the same as in ICRP30.

Nuclide(s)	Physical half-life	α	β_1 ($E_{av} < 0.2$)	β_2 ($E_{av} \geq 0.2$)	γ
^{232}Th	1.40×10^{10} y	4.00	----	----	----
$^{228}\text{Ra} + ^{228}\text{Ac}$	5.75 y	----	0.017	0.70	0.47
^{228}Th	1.91 y	5.35	----	----	0.0024
$^{224}\text{Ra} + \text{d}$	3.62 d	26.54	0.19	0.70	1.43

^aThe values shown under α , β_1 , β_2 , and γ are MeV per transformation of the nuclide or, if daughters are included, the parent nuclide.

Source Organ	Target			SEE(T ^s -S) (MeV g ⁻¹ transformation ⁻¹)			
	Organ	Mass(g)	W _T	²³² Th	²²⁸ Ra+ ²²⁸ Ac	²²⁸ Th	²²⁴ Ra+d
Lungs	Lungs	1000	0.12	8.00×10 ⁻²	7.20×10 ⁻⁴	1.07×10 ⁻¹	5.32×10 ⁻¹
Bone	BS ^a	120	0.03	1.67×10 ⁻¹	1.53×10 ⁻⁴	2.23×10 ⁻¹	1.11×10 ⁰
Bone	RM ^b	1500	0.12	1.33×10 ⁻²	1.20×10 ⁻⁴	1.78×10 ⁻²	8.86×10 ⁻²
Liver	Liver	1800	0.06	4.44×10 ⁻²	4.00×10 ⁻⁴	5.94×10 ⁻²	2.95×10 ⁻¹
Spleen	Spleen	180	0.06	4.44×10 ⁻¹	4.00×10 ⁻³	5.94×10 ⁻¹	2.95×10 ⁰
Kidneys	Kidneys	310	0.06	2.58×10 ⁻¹	2.32×10 ⁻³	3.45×10 ⁻¹	1.71×10 ⁰
Other	Other	61710	0.55	1.30×10 ⁻³	1.17×10 ⁻⁵	1.73×10 ⁻³	8.62×10 ⁻³
TB(Gamma)	TB ^c	70000	----	0.00×10 ⁰	2.35×10 ⁻⁶	0.00×10 ⁰	7.15×10 ⁻⁶

^aBS = bone surfaces.

^bRM = red marrow.

^cTB = total body.