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PUBLICATION RECORD

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07/10/2014	00	New technical information bulletin to detail how to evaluate chest counts, whole-body counts, and various types of urine samples after intakes of ^{232}Th. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Thomas R. LaBone.

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ACRONYMS AND ABBREVIATIONS

AMAD	activity median aerodynamic activity
Bq	becquerel
d	day
DOE	Department of Energy
hr	hour
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IRF	intake retention factor
M	moderate absorption type
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
pCi	picocurie
s	second
S	slow absorption type
SRDB Ref ID	Site Research Database Reference Identification (number)
TIB	technical information bulletin
yr	year
U.S.C.	United States Code
µm	micrometer
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document, the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy (DOE) facility” as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

1.1 PURPOSE

The purpose of this report is to detail how to evaluate chest counts, whole-body counts, and various types of urine samples after intakes of ^{232}Th. The computational methods for this TIB used the DCAL software and properly accounted for disequilibrium and independent kinetics. In addition, methods are offered that allow conservative approximations to the exact solutions to be made with existing Project software [i.e., Integrated Modules for Bioassay Analysis (IMBA)].

1.2 BACKGROUND

Thorium-232 is a long-lived radionuclide that has a decay chain with 10 progeny that are themselves radioactive. Figure 1-1 shows the first eight members of the chain. Evaluating bioassay data to calculate intakes of ^{232}Th and its progeny can be one of the most challenging tasks in internal dosimetry. The primary challenges are caused by disequilibrium of the ^{232}Th decay chain and independent biokinetics of the members of the decay chain.

$$^{232}\mathrm{Th} \xrightarrow{1.405\times10^{10}\,\mathrm{yr}} {}^{228}\mathrm{Ra} \xrightarrow{5.75\,\mathrm{yr}} {}^{228}\mathrm{Ac} \xrightarrow{6.13\,\mathrm{hr}} {}^{228}\mathrm{Th}$$

$$^{228}\mathrm{Th} \xrightarrow{1.91\,\mathrm{yr}} {}^{224}\mathrm{Ra} \xrightarrow{3.62\,\mathrm{d}} {}^{220}\mathrm{Rn} \xrightarrow{55.6\,\mathrm{s}} {}^{216}\mathrm{Po} \xrightarrow{0.146\,\mathrm{s}} {}^{212}\mathrm{Pb} \xrightarrow{10.6\,\mathrm{hr}}$$

Figure 1-1. First eight members of the ^{232}Th decay chain.

Equilibrium versus Disequilibrium

Thorium-232 confined in one place with its progeny will eventually come into “secular equilibrium” (i.e., the activity of all members of the decay chain will be equal to that of the parent ^{232}Th). As this document shows, equilibrium makes it relatively easy to estimate intakes from bioassay data.

Chemical processing separates the members of the decay chain based on what element they are, disrupt this equilibrium, and cause the progeny to be present in varying amounts that change over time. This “disequilibrium” complicates evaluation of bioassay data because dose reconstructors usually have to specify the nature of the disequilibrium to evaluate bioassay data.

Shared versus Independent Kinetics

“Shared kinetics” refers to the assumption that all members of the decay chain have the same biokinetics as ^{232}Th (i.e., all progeny are transported, deposited, and retained in the body just like the parent). Shared kinetics are used in the International Commission on Radiological Protection (ICRP) Publication 30 biokinetic models for thorium (ICRP 1979–1988).

“Independent kinetics” refers to the assumption that all members of the decay chain have biokinetics based on the element. For example, ^{232}Th has the biokinetics of thorium until it decays to ^{228}Ra, at which point is has the biokinetics of radium (thorium and radium have very different biokinetics). Independent kinetics are used in the newer ICRP Publication 68 biokinetic models (ICRP 1995), which are the models the NIOSH Project uses to evaluate bioassay data. Independent kinetics complicates the evaluation of bioassay data because IMBA does not support independent kinetics for the ^{232}Th chain. However, the DCAL[1] software does properly account for independent kinetics and was used for this analysis to obtain exact solutions.

2.0 EQUILIBRIUM AND SHARED KINETICS

2.1 CHEST AND WHOLE-BODY COUNTS

Thorium-232 and ^{228}Th do not emit photon radiation that is useful for quantifying the thorium in the body with in vivo bioassay (chest or whole-body counting). For this reason, in vivo bioassay for ^{232}Th is often performed by quantifying the activity of the ^{228}Ac or ^{212}Pb progeny in the body and then calculating the amount of ^{232}Th (and relatively long-lived progeny ^{228}Ra and ^{228}Th) present by assuming the material is in secular equilibrium. This is considered to be a reasonable approach when:

- The inhaled thorium has been locked in an insoluble physical matrix for a long period (e.g., for natural thorium mined from the ground), and
- The inhaled thorium particulate does not dissolve in the lungs to any great extent.

Example 2-1

For example, assume that a person inhaled 1 nCi of 5-µm activity median aerodynamic activity (AMAD) Type S ^{232}Th in equilibrium with its progeny. IMBA and DCAL can be used to calculate[2] the ^{232}Th chest burden, denoted here as $q_{th232}(t)$, where t is time in days. At 100 days after the intake it would be:

$$q_{th232}(100) = 3.670\text{E-}02\,\text{nCi} \ \text{(per nCi intake of } ^{232}\text{Th)} \tag{2-1}$$

Note that the intake retention fraction (IRF), denoted here as $m_{th232}(t)$, is:

$$m_{th232}(100) = \frac{q_{th232}(100)}{1\text{nCi}} \tag{2-2}$$

at t = 100 days after the intake. The discussion in this report uses both IRFs and burdens to develop the concepts.

Under the stated conditions, equilibrium implies that the chest burdens of all the progeny of ^{232}Th, including that of ^{212}Pb (q_{pb212}), are the same as the parent ^{232}Th chest burden:

$$q_{pb212}(100) = 3.670\text{E-}02\,\text{nCi} \ \text{(per nCi intake of } ^{232}\text{Th)} \tag{2-3}$$

[1] http://www.epa.gov/radiation/assessment/dcal.html.
[2] DCAL was used for all calculations for this report. DCAL and IMBA produce similar results in situations where both are applicable. For example, the burden per unit intake IMBA calculated in this case is 3.666E-2 nCi per nCi intake of ^{232}Th.

If a chest burden of 10 nCi of ^{212}Pb was measured at 100 days after an acute inhalation intake, the intake of ^{232}Th (I_{th232}) is:

$$I_{th232} = \left(\frac{10\,\text{nCi}}{m_{pb212}(100)}\right) = \left(\frac{10\,\text{nCi}}{m_{th232}(100)}\right) = \left(\frac{10\,\text{nCi}}{3.67\text{E-}2}\right) = 272.5\,\text{nCi} \tag{2-4}$$

The intake of each progeny of ^{232}Th is equal to the intake of ^{232}Th. For a measured a chest burden of 10 nCi of ^{228}Ac instead of 10 nCi of ^{212}Pb, the resulting ^{232}Th intake estimate would be the same as above. The evaluation of whole-body count data is completely analogous to the evaluation of chest count data, the only difference being that whole-body burdens are substituted for the chest burdens.

2.2 URINE

Thorium in urine is typically quantified using one of the following three analyses:

- Isotopic thorium (^{232}Th and ^{228}Th activities reported separately),
- Total thorium (sum of ^{232}Th and ^{228}Th activity reported), and
- ^{228}Th (only ^{228}Th activity reported).

Assuming equilibrium and shared kinetics makes the evaluation of thorium urine bioassay results relatively straightforward because the ^{232}Th and/or ^{228}Th are measured directly.

Example 2-2

Assume that a person inhaled 10 pCi of 5-µm AMAD Type S ^{232}Th in equilibrium with its progeny. We can calculate that at 100 days after this intake the person would have a 24-hour urine sample containing:

$$q_{th232}(100) = 3.650\text{E-}06\,\text{pCi} \text{ (per 10 pCi intake of } ^{232}\text{Th)} \tag{2-5}$$

Note that this is an incremental 24-hour urine sample and by convention it was <u>completed</u> at 100 days after the intake. If 10 pCi of ^{232}Th is measured in the urine, the intake of ^{232}Th is:

$$I_{th232} = \left(\frac{10\,\text{pCi}}{m_{th232}(100)}\right) = \left(\frac{10\,\text{pCi}}{3.650\text{E-}07}\right) = 2.740\text{E+}07\,\text{pCi} \tag{2-6}$$

where m_{th232} is the IRF for ^{232}Th in a 24-hour urine sample.

Example 2-3

If 10 pCi of ^{228}Th is measured in the urine, the intake of ^{232}Th is:

$$I_{th232} = \left(\frac{10\,\text{pCi}}{m_{th228}(100)}\right) = \left(\frac{10\,\text{pCi}}{m_{th232}(100)}\right) = \left(\frac{10\,\text{pCi}}{3.650\text{E-}7}\right) = 2.740\text{E+}07\,\text{pCi} \tag{2-7}$$

Example 2-4

If 10 pCi of total thorium is measured in the urine, the intake of total thorium is:

$$I_{th} = \left(\frac{5\,\text{pCi}}{m_{th232}(100)}\right) + \left(\frac{5\,\text{pCi}}{m_{th228}(100)}\right) == \left(\frac{10\,\text{pCi}}{m_{th232}(100)}\right) = 2.740\text{E+07}\,\text{pCi} \tag{2-8}$$

This calculation assumes that half of the total thorium activity in the urine is ^{232}Th and half is ^{228}Th. The intakes of ^{232}Th and ^{228}Th are therefore:

$$I_{th232} = I_{th228} = 0.5 I_{th} = 1.370\text{E+07}\,\text{pCi} \tag{2-9}$$

where I_{th} is the total thorium intake activity.

3.0 DISEQUILIBRIUM AND SHARED KINETICS

3.1 CHEST AND WHOLE-BODY COUNTS

Thorium that has been chemically purified consists primarily of ^{232}Th and ^{228}Th. Progeny that are not isotopes of thorium are absent immediately after purification and begin to grow in. The progeny can exist in various degrees of disequilibrium with the parent ^{232}Th depending on the timing and number of separations. For example, the plot in Figure 3-1 shows the activity of ^{228}Th present as a function of time after a chemical separation that removes all of the nonthorium isotopes. Immediately after the separation the ratio of ^{228}Th to ^{232}Th is 1:1, but it decreases to a minimum of 1:0.422 at 4.55 years after separation. This behavior is the result of the ^{228}Ra being removed from the material and its subsequent in growth.

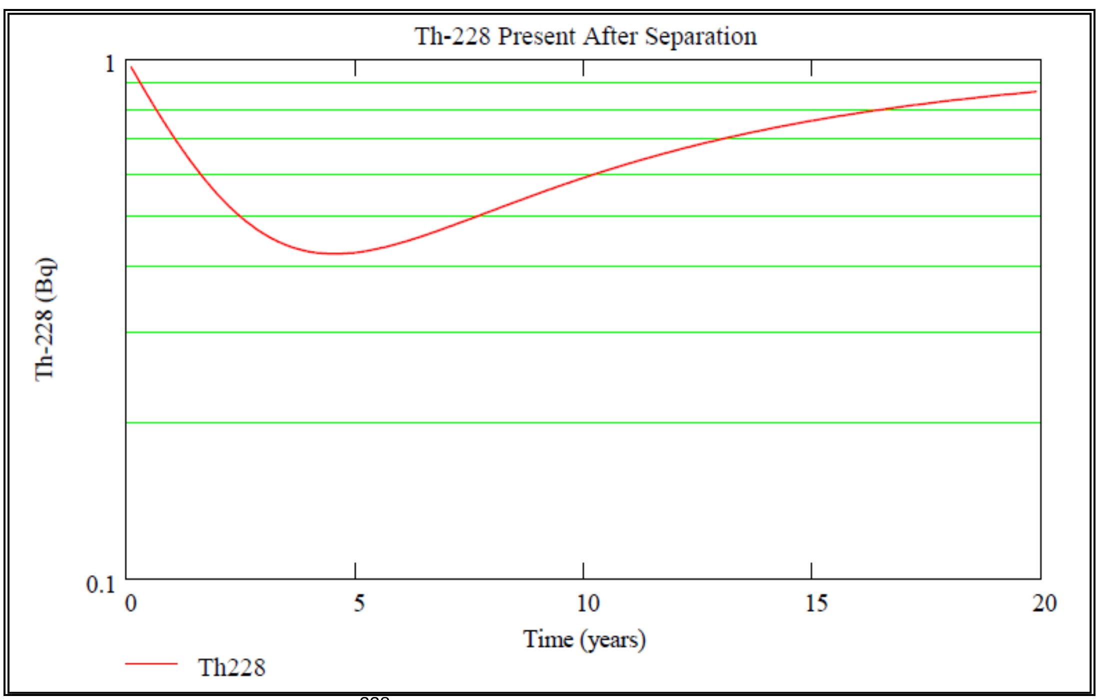

Figure 3-1. Activity (Bq) of ^{228}Th (red line) present as a function of time after chemical purification of 1 Bq of ^{232}Th in equilibrium with its progeny.

The ingrowth curves for ^{228}Ra and ^{224}Ra are shown in Figure 3-2. These two progeny are important because ^{212}Pb (which can be measured in vivo) is in equilibrium with the ^{224}Ra, and ^{228}Ac (also in vivo measurable) is in equilibrium with the ^{228}Ra. Therefore, we can use ^{212}Pb to quantify the ^{228}Th present and ^{228}Ac to quantify the ^{228}Ra present. In addition, note that the minimum in the ^{228}Th:^{232}Th curve in Figure 3-1 is always greater than zero, whereas the minimum of the ^{228}Ra:^{232}Th curve in Figure 3-2 is zero. The practical consequences of all this are:

- If there is ^{212}Pb present, there is always ^{228}Th and ^{232}Th present. Even though the exact activity of ^{232}Th is unknown, it is feasible to come up with a conservative estimate based on the ^{212}Pb.
- If there is ^{228}Ac present, there might or might not be ^{232}Th present because the ^{228}Ra parent of ^{228}Ac has a half-life long enough to exist independently of the ^{232}Th. It is difficult to come up with a conservative estimate of the ^{232}Th based on the ^{228}Ac because there is no nonzero minimum in the ingrowth curve.

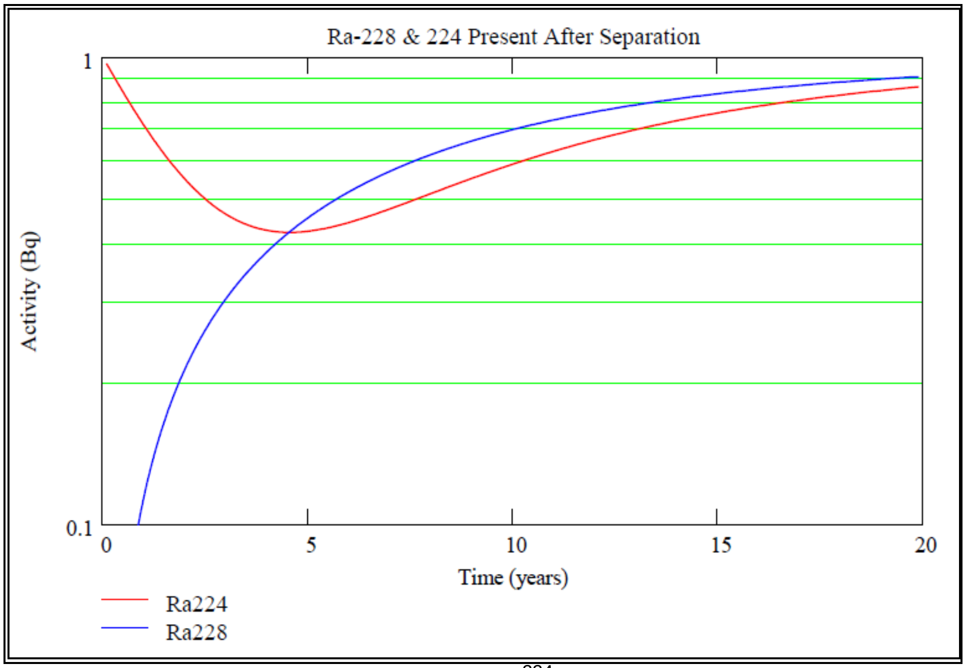

Figure 3-2. Radium-228 (blue line) and ^{224}Ra (red line) present as a function of time after chemical purification of 1 Bq of ^{232}Th in equilibrium with its progeny. Note that the ^{224}Ra curve is basically the same as the ^{228}Th curve in Figure 3-1.

In summary, to properly interpret a ^{212}Pb or ^{228}Ac chest count in terms of the ^{232}Th intake, the dose reconstructor needs to know something about the relative amounts of the ^{232}Th progeny in the material. This information is usually derived from a knowledge of the separation history of the material and a liberal application of the Bateman equations. To facilitate dose reconstructions based on ^{212}Pb, four standard thorium mixtures are used (see Appendix A):

- Unseparated (equilibrium) thorium, which has a 1:1 ^{228}Th to ^{232}Th ratio;
- Single-separated thorium, which has a 0.42:1 ^{228}Th to ^{232}Th ratio;
- Double-separated thorium, which has a 0.26:1 ^{228}Th to ^{232}Th ratio; and
- Triple-separated thorium, which has a 0.19:1 ^{228}Th to ^{232}Th ratio.

There are two important points to make about these standard mixtures. First, once a mixture is selected for a particular application, it is assumed to be a constant and does not change as a function of time. For example, if a worker is assumed to be chronically exposed to triple-separated thorium in a facility from 1980 to 1995, then the same mixture applies for the entire exposure period; that is, there is no ingrowth of ^{228}Th during the 15 years. Second, the mixtures define the relative amounts of ^{232}Th and ^{228}Th but not any of the other members of the decay chain. More specifically, these thorium mixtures do not contain any ^{228}Ra.

Analogous standard thorium mixtures for evaluating ^{228}Ac chest counts are discussed in Attachment A. In practice, the age of the thorium (i.e., the years since separation) must be specified to interpret an ^{228}Ac chest count.

Example 3-1

Assume that after a chemical separation the thorium is fabricated into an insoluble material, which is inhaled by a worker. Assuming the worker inhaled 5-µm AMAD Type S single-separation thorium, the exact expression for the ^{212}Pb chest burden of 10 nCi is given by:

$$q_{pb212}(100) = 10\,\text{nCi} = I_{\text{th232}} m_{\text{pbth232}}(100) + I_{\text{th228}} m_{\text{pbth228}}(100) \tag{3-1}$$

where $m_{\text{pbth228}}(t)$ is the IRF for ^{212}Pb that grows in from the ^{228}Th intake and $m_{\text{pbth232}}(t)$ is the IRF for the ^{212}Pb that grows in from the ^{232}Th. Based on the discussion above and that in Attachment A, the following assumptions are used:

$$m_{\text{pbth228}}(t) = m_{\text{th228}}(t) \tag{3-2}$$

$$m_{\text{pbth232}}(t) = 0\ ^{3} \tag{3-3}$$

$$\frac{I_{\text{th228}}}{I_{\text{th232}}} = 0.42 \tag{3-4}$$

Therefore, the intake of ^{228}Th simplifies to:

$$I_{\text{th228}} = \left(\frac{10\,\text{nCi}}{m_{\text{th228}}(100)}\right) = \left(\frac{10\,\text{nCi}}{(3.320\text{E-02})}\right) = 3.012\text{E+02}\,\text{nCi} \tag{3-5}$$

The ^{232}Th intake is equal to 301.2 ÷ 0.42 = 717.2 nCi, but the intakes of all other ^{232}Th progeny are 0 nCi. This intake estimate is relatively insensitive to the time that has elapsed since separation (i.e., the age of the thorium) and is a conservative intake estimate as long as the thorium has only been processed once.

Example 3-2

If we had measured 10 nCi of ^{228}Ac 100 days after an acute inhalation of thorium (thorium in general), the exact expression for the ^{228}Ac chest burden would be:

$$10\,\text{nCi} = I_{\text{th232}} m_{\text{acth232}}(100) + I_{\text{ra228}} m_{\text{acra228}}(100) \tag{3-6}$$

where $m_{\text{acth232}}(t)$ is the IRF for ^{228}Ac that grows in from the ^{232}Th intake, and $m_{\text{acra228}}(t)$ is the IRF for ^{228}Ac that grows in from the ^{228}Ra intake.

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[3] Because of the long physical half life of ^{232}Th there is negligible ingrowth of ^{212}Pb.

Single-separation thorium is assumed to contain no ^{228}Ra, so the second term is equal to zero:

$$10\,\text{nCi} = I_{\text{th232}} m_{\text{acth232}}(100) \tag{3-7}$$

The intake is therefore:

$$I_{\text{th232}} = \left(\frac{10\,\text{nCi}}{m_{\text{acth232}}(100)}\right) = \left(\frac{10\,\text{nCi}}{1.190\text{E-03}}\right) = 8.403\text{E+03}\,\text{nCi} \tag{3-8}$$

This is a rather large intake of ^{232}Th given a modest 10-nCi ^{228}Ac chest burden. The IRF for ^{228}Ra/^{228}Ac that grows in from ^{232}Th is very sensitive the time that has elapsed since separation, and there is no conservative time that can be specified that is applicable for all situations. This means that the time since separation has to be specified in the evaluation of ^{228}Ac chest count data. This is in contrast to the evaluation of ^{212}Pb chest counts, where conservative mixtures and times can be specified that are applicable to all situations.

3.2 URINE BIOASSAY

The standard disequilibrium mixtures are easily incorporated into the urine bioassay calculations.

Example 3-3

Continuing the previous example with Type S single-separation thorium, if 10 pCi of ^{232}Th is measured in the urine, the intakes of ^{232}Th and ^{228}Th are:

$$I_{\text{th232}} = \left(\frac{10\,\text{pCi}}{m_{\text{th232}}(100)}\right) = 2.740\text{E+07}\,\text{pCi} \tag{3-9}$$

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 1.151\text{E+07}\,\text{pCi} \tag{3-10}$$

Example 3-4

If 10 pCi of ^{228}Th is measured in the urine, the intakes of ^{228}Th and ^{232}Th are:

$$I_{\text{th228}} = \left(\frac{10\,\text{pCi}}{m_{\text{th228}}(100)}\right) = \left(\frac{10\,\text{pCi}}{3.310\text{E-07}}\right) = 3.021\text{E+07}\,\text{pCi} \tag{3-11}$$

and:

$$I_{\text{th232}} = \frac{I_{\text{th228}}}{0.42} = 7.193\text{E+07}\,\text{pCi} \tag{3-12}$$

Example 3-5

There are 10 pCi of total thorium measured in the urine. Given that:

$$I_{\text{th232}} m_{\text{th232}}(100) + I_{\text{th228}} m_{\text{th228}}(100) = 10\,\text{pCi} \tag{3-13}$$

and:

$$\frac{I_{\text{th228}}}{I_{\text{th232}}} = 0.42 \tag{3-14}$$

then the ^{232}Th intake is :

$$\begin{aligned} I_{\text{th232}} &= \frac{10\,\text{pCi}}{m_{\text{th232}}(100) + 0.42 m_{\text{th228}}(100)} \\ &= \frac{10\,\text{pCi}}{(3.650\text{E-07}) + 0.42(3.310\text{E-07})} \\ &= 1.984\text{E+07}\,p\text{Ci} \end{aligned} \tag{3-15}$$

The intake of ^{228}Th is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 8.333\text{E+06}\,\text{pCi} \tag{3-16}$$

4.0 EXACT CALCULATIONS ASSUMING INDEPENDENT KINETICS

Implicit in the calculations above is the assumption that the ^{232}Th and its progeny remain together in the body. This assumption of shared kinetics is reasonable for insoluble thorium particulates in the lung, but once the thorium matrix dissolves and the members of the decay chain become subject to the metabolic processes of the body this assumption is not sufficient over time[4]. The current ICRP biokinetic models for the ^{232}Th decay chain account for this by assuming that each element (especially thorium, radium, and radon) follows its own biokinetic model once it is released from or born outside of an insoluble matrix. The progeny of the ^{232}Th decay chain are said to have independent kinetics.

All of the calculations up to this point can be performed with burdens from IMBA. From a practical point of view, independent kinetics significantly complicates the calculation of IRFs and evaluation of bioassay data because IMBA employs shared kinetics rather than independent kinetics and can no longer be used in all cases.

The DCAL software is capable of using independent kinetics to calculate burdens of ^{212}Pb, ^{228}Ac, and ^{228}Th that are the decay products of radionuclides ahead of them in the decay chain. For example, chest burdens that were calculated with DCAL for unit acute inhalation intakes of 5-µm AMAD Type S materials (^{232}Th, ^{228}Ra, ^{228}Th, ^{224}Ra) are shown in Figures 4-1 through 4-4.

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[4] All of the ICRP Publication 30 biokinetic models except for tellurium assumed shared kinetics (ICRP 1979–1988).

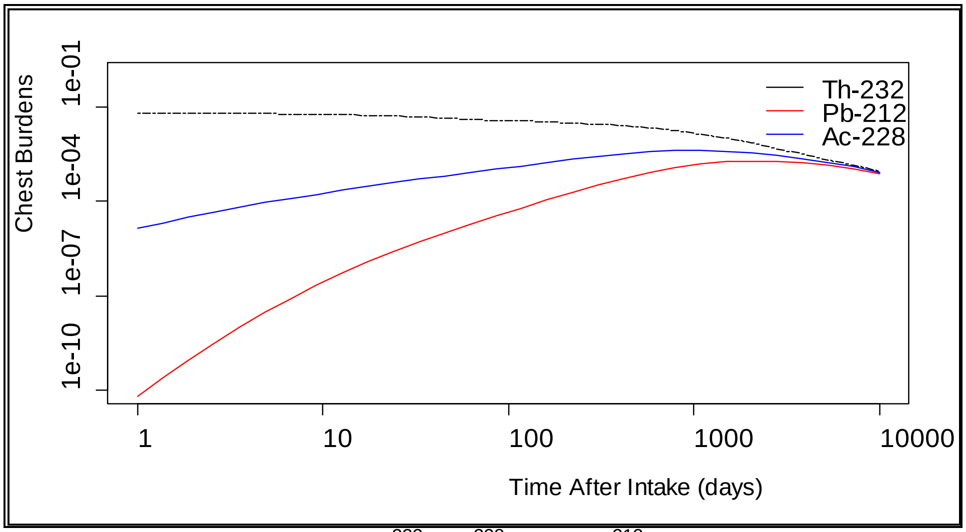

Figure 4-1. Chest burdens of ^{232}Th, ^{228}Ac, and ^{212}Pb after a unit acute inhalation intake of pure Type S ^{232}Th.

To further refine the calculations, assume that ^{232}Th in secular equilibrium with its progeny was inhaled. Of primary concern here are the biokinetics of ^{232}Th through ^{212}Pb, ^{228}Ra through ^{212}Pb, and ^{228}Th through ^{212}Pb. All other unsupported progeny in the initial intake have half-lives that are short enough to limit their contribution to the observed ^{212}Pb whole-body burden except in the first couple of days after the inhalation. To confirm this, the analysis also examined the ^{224}Ra through ^{212}Pb decay chain, which should be the most significant of the short-lived chains because of the half-life of ^{224}Ra. The following discussion provides examples.

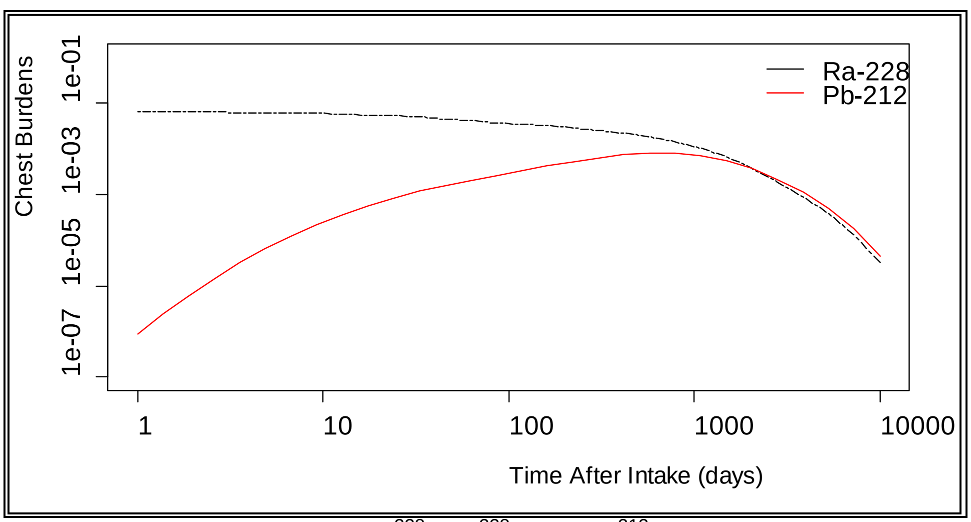

Figure 4-2. Chest burdens of ^{228}Ra, ^{228}Ac, and ^{212}Pb after a unit acute inhalation intake of pure Type S ^{228}Ra. The ^{228}Ac activity is equal to the ^{228}Ra activity.

Figure 4-3. Chest burdens of ^{228}Th and ^{212}Pb after a unit acute inhalation intake of pure Type S ^{228}Th.

Example 4-1

If the measured chest burden of ^{212}Pb at 100 days after an acute inhalation intake of 5-µm AMAD Type S material is 10 nCi, what would be the intakes assuming they consisted of four different pure materials?

The quantity of ^{212}Pb present in the chest at time *t* after a unit intake of pure ^{232}Th is denoted by $m_{\text{pbth232}}(t)$.

Therefore:

$$m_{\text{pbth232}}(100) = 4.640\text{E-}05 \tag{4-1}$$

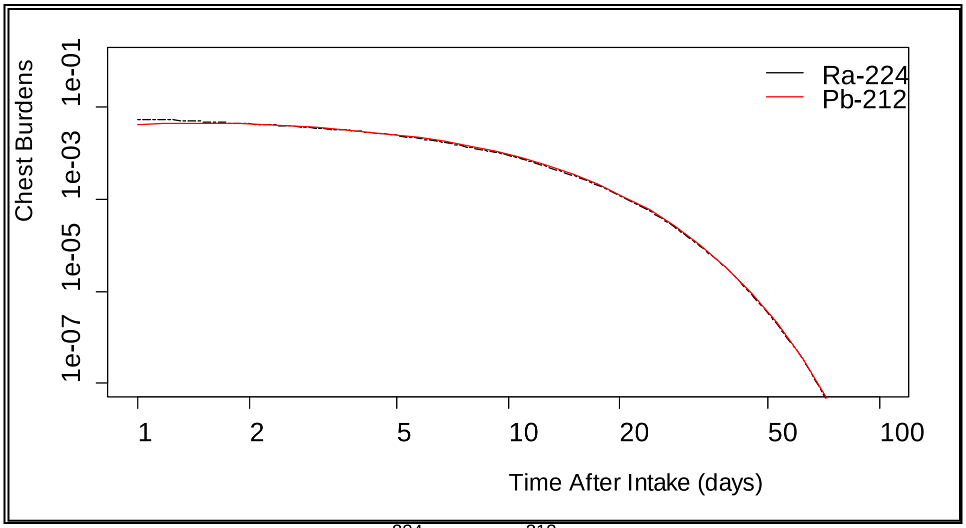

Figure 4-4. Chest burdens of ^{224}Ra and ^{212}Pb after a unit acute inhalation intake of pure Type S ^{224}Ra.

and:

$$I_{\text{th232}} = \left(\frac{10\,\text{nCi}}{m_{\text{pbth232}}(100)} \right) = \frac{10\,\text{nCi}}{4.640\text{E-}05} = 2.155\text{E+}05\,\text{nCi} \tag{4-2}$$

For comparison, what would the intake be if the ^{212}Pb and ^{232}Th were in secular equilibrium, exhibited shared kinetics, and no ^{220}Rn was lost from the body?:

$$I = \frac{10\,\text{nCi}}{m_{\text{th232}}(100)} = \frac{10\,\text{nCi}}{3.670\text{E-}02} = 2.725\text{E+}02\,\text{nCi} \tag{4-3}$$

Note that the IRF in this equation is for the ^{232}Th because the ^{212}Pb is assumed to be present in a quantity equal to that of the ^{232}Th. It is of interest to note that this simplistic assumption results in an intake estimate that is lower than the exact estimate by a factor of:

$$\frac{3.670\text{E-}02}{4.640\text{E-}05} \approx 790 \tag{4-4}$$

Here are the exact calculations for the other intakes:

$$I_{\text{ra228}} = \frac{10\,\text{nCi}}{m_{\text{pbra228}}(100)} = \frac{10\,\text{nCi}}{2.930\text{E-03}} = 3.413\text{E+03}\,\text{nCi} \quad (4\text{-}5)$$

$$I_{\text{th228}} = \frac{10\,\text{nCi}}{m_{\text{pbth228}}(100)} = \frac{10\,\text{nCi}}{3.060\text{E-02}} = 3.268\text{E+02}\,\text{nCi} \quad (4\text{-}6)$$

$$I_{\text{ra224}} = \frac{10\,\text{nCi}}{m_{\text{pbra224}}(100)} = \frac{10\,\text{nCi}}{2.280\text{E-10}} = 4.386\text{E+10}\,\text{nCi} \quad (4\text{-}7)$$

The calculations for whole-body counts are the same as above except whole-body burdens per unit intake are substituted for the chest-burdens per unit intake.

Example 4-2

For the same 10 nCi ^{212}Pb chest burden, what would the intake be if the source material was ^{232}Th in equilibrium with its progeny?:

$$I_{\text{th232}}m_{\text{pbth232}}(100) + I_{\text{ra228}}m_{\text{pbra228}}(100) + I_{\text{th228}}m_{\text{pbth228}}(100) = 10\,\text{nCi} \quad (4\text{-}8)$$

The intake of ^{228}Ra and ^{228}Th are assumed to equal the intake of ^{232}Th because the material is in equilibrium, so this can be simplified to:

$$I_{\text{th232}}\left[m_{\text{pbth232}}(100) + m_{\text{pbra228}}(100) + m_{\text{pbth228}}(100)\right] = 10\,\text{nCi} \quad (4\text{-}9)$$

which can be rearranged to give the intake:

$$I_{\text{th232}} = \frac{10\,\text{nCi}}{m_{\text{pbth232}}(100) + m_{\text{pbra228}}(100) + m_{\text{pbth228}}(100)} = 2.978\text{E+02}\,\text{nCi} \quad (4\text{-}10)$$

This means that 297.8 nCi of ^{232}Th and 297.8 nCi of each of its progeny was inhaled. The inclusion of ^{224}Ra does not change the intake estimate because it contributes practically no ^{212}Pb at t = 100 days after intake:

$$I = \frac{10\,\text{nCi}}{m_{\text{pbth232}}(100) + m_{\text{pbra228}}(100) + m_{\text{pbth228}}(100) + m_{\text{pbra224}}(100)} = 2.978\text{E+02}\,\text{nCi} \quad (4\text{-}11)$$

For the purpose of evaluating ^{212}Pb in vivo counts, only the long-lived radionuclides ^{232}Th, ^{228}Ra, and ^{228}Th in the source term need to be specified. Attributing any ^{212}Pb contributed by short-lived progeny like ^{224}Ra would result in an overestimate of the intakes of the dosimetrically significant ^{232}Th, ^{228}Ra, and ^{228}Th.

Example 4-3

What would the intake be if the source material was ^{232}Th with the activity of the ^{228}Ra in the source material being one-half of the ^{232}Th activity and the activity of the ^{228}Th in the source material being one-quarter of the ^{232}Th activity?

$$I_{\text{th232}}\left[m_{\text{pbth232}}(100)+0.5m_{\text{pbra228}}(100)+0.25m_{\text{pbth228}}(100)\right]=10\,\text{nCi} \quad (4\text{-}12)$$

$$I_{\text{th232}}=\frac{10\,\text{nCi}}{m_{\text{pbth232}}(100)+0.5m_{\text{pbra228}}(100)+0.25m_{\text{pbth228}}(100)}=1.092\text{E+03}\,\text{nCi} \quad (4\text{-}13)$$

This means the inhalation intake consisted of 1,092 nCi of ^{232}Th, 1,092 ÷ 2 = 546 nCi of ^{228}Ra, and 1,032 ÷ 4 = 273 nCi of ^{228}Th. This result is unchanged with the inclusion of ^{224}Ra.

Example 4-4

What would the intake be if the source material was ^{232}Th in equilibrium with its progeny and the measured chest burden was 10 nCi of ^{228}Ac? Analogous to the way we looked at the ^{212}Pb burdens, we have:

$$I_{\text{th232}}m_{\text{acth232}}(100)+I_{\text{acra228}}m_{\text{pbra228}}=10\,\text{nCi} \quad (4\text{-}14)$$

The intake of ^{228}Ra is assumed to equal the intake of ^{232}Th, so this can be simplified to:

$$I_{\text{th232}}\left[m_{\text{acth232}}(100)+m_{\text{acra228}}(100)\right]=10\,\text{nCi} \quad (4\text{-}15)$$

which can be rearranged to give the intake:

$$I_{\text{th232}}=\frac{10\,\text{nCi}}{m_{\text{acth232}}(100)+m_{\text{acra228}}(100)}=\frac{10\,\text{nCi}}{1.19E\text{-}3+3.55E\text{-}2}=2.726\text{E+02}\,\text{nCi} \quad (4\text{-}16)$$

This means that 272.6 nCi of ^{232}Th and 272.6 nCi of each of its progeny was inhaled.

4.1 URINE BIOASSAY

Plots of ^{232}Th, ^{228}Ra, and ^{228}Th urinary excretion curves calculated with DCAL for unit acute inhalation intakes of 5-µm AMAD Type S materials are shown in Figures 4-5 through 4-7.

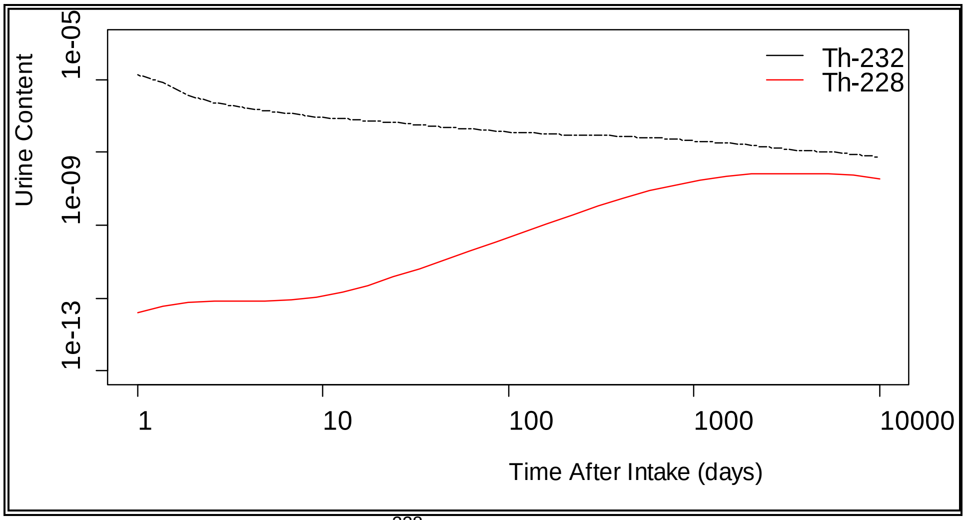

Figure 4-5. Thorium-232 and ^{228}Th in a 24-hour incremental urine sample after a unit acute inhalation intake of pure Type S ^{232}Th. Note that IRFs from IMBA can be used to model ^{232}Th in urine after a ^{232}Th intake.

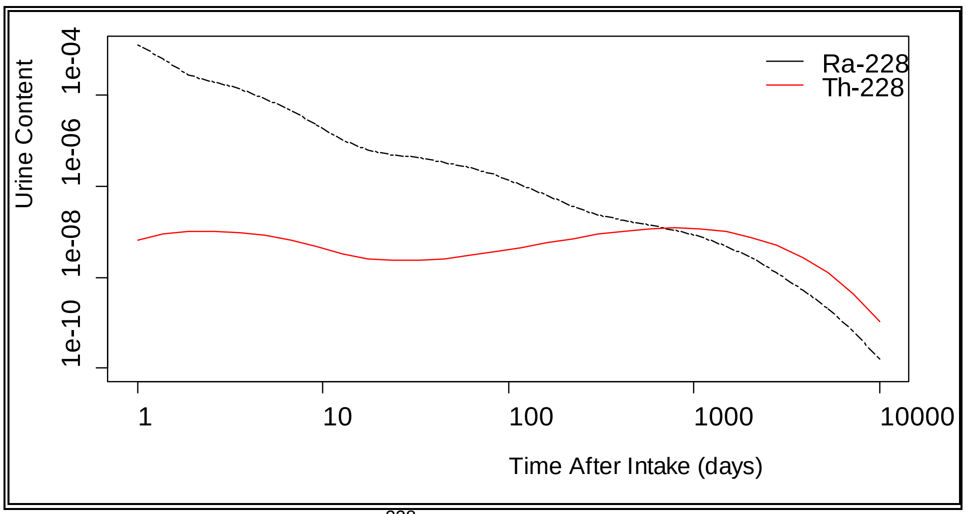

Figure 4-6. Radium-228 and ^{228}Th in a 24-hour incremental urine sample after a unit acute inhalation intake of pure Type S ^{228}Ra.

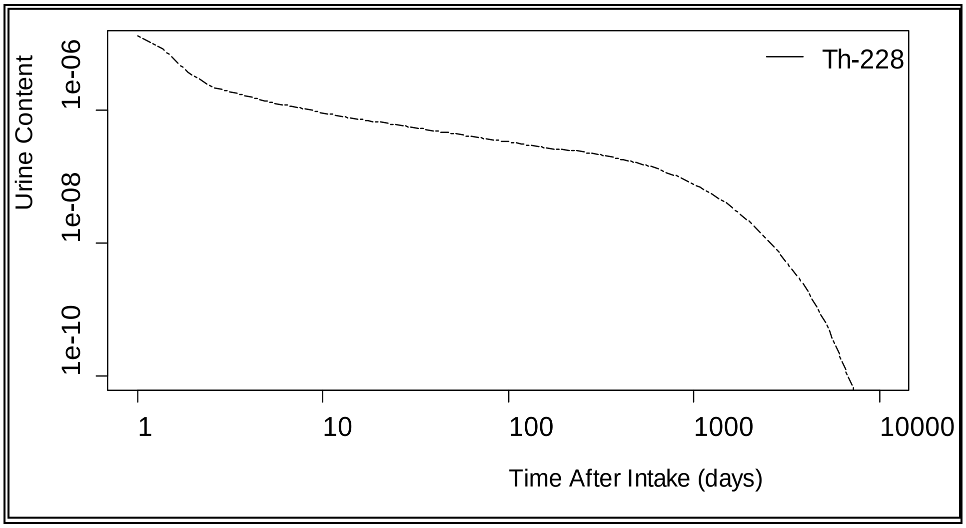

Figure 4-7. Thorium-228 in a 24-hour incremental urine sample after a unit acute inhalation intake of pure Type S ^{228}Th. Note that IRFs from IMBA can be used to model ^{228}Th in urine after a ^{228}Th intake.

Example 4-5

If 10 pCi of ^{232}Th is measured in the urine at 100 days after an acute inhalation intake of 5-µm AMAD Type S material, the intake of ^{232}Th is:

$$I_{\text{th232}} = \left(\frac{10\,\text{pCi}}{m_{\text{th232}}(100)} \right) = 2.740\text{E+07}\,\text{pCi} \tag{4-17}$$

To get the intakes of the other members of the decay chain like ^{232}Th we have to assume a particular mixture. For single-separation thorium the ^{228}Th intake is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 1.151\text{E+07}\,\text{pCi} \tag{4-18}$$

Note that IRFs from IMBA can be used to evaluate ^{232}Th in urine.

Example 4-6

Assume that 10 pCi of ^{228}Th is measured in the urine after an intake of single-separation thorium. It is instructive to look at the excretion function like this:

$$\left[I_{\text{th232}} m_{\text{thth232}}(100) + I_{\text{th228}} m_{\text{th228}}(100) \right] = 10\,\text{pCi} \tag{4-19}$$

Note that ^{228}Ra does not contribute to the ^{228}Th in the urine because it was all removed in the separation process. Given that $m_{\text{thth232}}(100)$ is the amount of ^{228}Th in the urine at 100 days after an acute inhalation intake of pure ^{232}Th, the intake of ^{228}Th is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} \tag{4-20}$$

which gives:

$$I_{\text{th232}} \left[m_{\text{thth232}}(100) + 0.42 m_{\text{th228}}(100) \right] = 10\,\text{pCi} \tag{4-21}$$

Rearranging and solving this equation gives the ^{232}Th intake:

$$\begin{aligned} I_{\text{th232}} &= \left(\frac{10\,\text{pCi}}{m_{\text{thth232}}(100) + 0.42 m_{\text{th228}}(100)} \right) \\ &= \left(\frac{10\,\text{pCi}}{(4.640\text{E-}10) + 0.42(3.310\text{E-}07)} \right) \\ &= 7.169\text{E}+07\,\text{pCi} \end{aligned} \quad (4\text{-}22)$$

The ^{228}Th intake is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 3.011\text{E+}07\,\text{pCi} \quad (4\text{-}23)$$

Example 4-7

Finally, what are the ^{232}Th and ^{228}Th intakes if there is a measured 10 pCi of total thorium in the urine? As before, the excretion function is:

$$\left[I_{\text{th232}} m_{\text{th232}}(100) + I_{\text{th232}} m_{\text{thth232}}(100) + I_{\text{th228}} m_{\text{th228}}(100) \right] = 10\,\text{pCi} \quad (4\text{-}24)$$

Assuming single-separation thorium, this simplifies to:

$$I_{\text{th232}} \left[m_{\text{th232}}(100) + m_{\text{thth232}}(100) + 0.42 m_{\text{th228}}(100) \right] = 10\,\text{pCi} \quad (4\text{-}25)$$

Rearranging and solving this equation gives the ^{232}Th intake:

$$\begin{aligned} I_{\text{th232}} &= \frac{10\,\text{pCi}}{m_{\text{th232}}(100) + m_{\text{thth232}}(100) + 0.42 m_{\text{th228}}(100)} \\ &= \frac{10\,\text{pCi}}{(3.650\text{E-}07) + (4.640\text{E-}10) + 0.42(3.310\text{E-}07)} \\ &= 1.982\text{E+}07\,\text{pCi} \end{aligned} \quad (4\text{-}26)$$

The ^{228}Th intake is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 8.325\text{E+}06\,\text{pCi} \quad (4\text{-}27)$$

5.0 CHRONIC INTAKES

DCAL does not generate burdens that result from constant chronic intakes. Methods for calculating chronic intake burdens from acute intake burdens are discussed in Appendix B. The results of these calculations are chronic intake IRFs (denoted by $\tilde{m}$) such as the one shown below for ^{212}Pb in the chest after an intake of pure ^{232}Th:

$$\tilde{m}_{\text{pbth232}}(t,T) \qquad t \geq T$$

where

T = length of chronic intake period
t = time that the ^{212}Pb chest burden is measured relative to start of chronic intake

This IRF is interpreted as being the ratio of the amount of ^{212}Pb present in the chest at *t* days after the start of the chronic intake to the total amount of ^{232}Th inhaled over the *T*-day chronic intake period. This in contrast to IMBA, where the IRF is interpreted as being the ratio of the amount of ^{212}Pb present in the chest at *t* days after the start of the chronic intake to the intake rate of ^{232}Th over the *T*-day chronic intake period.

Example 5-1

As an example, assume a 10-nCi chest burden of ^{212}Pb at 365 days after the start of a 100-day chronic inhalation intake of 5-µm AMAD Type S material. What would be the total intakes if they consisted of the four different pure materials?

$$I_{\mathrm{th232}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{pbth232}}(365{,}100)} = \frac{10\,\mathrm{nCi}}{3.475\text{E-}04} = 2.878\text{E+}04\,\mathrm{nCi} \tag{5-1}$$

$$I_{\mathrm{ra228}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{pbra228}}(365{,}100)} = \frac{10\,\mathrm{nCi}}{6.339\text{E-}03} = 1.578\text{E+}03\,\mathrm{nCi} \tag{5-2}$$

$$I_{\mathrm{th228}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{th228}}(365{,}100)} = \frac{10\,\mathrm{nCi}}{1.877\text{E-}02} = 5.327\text{E+}02\,\mathrm{nCi} \tag{5-3}$$

$$I_{\mathrm{ra224}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{ra224}}(365{,}100)} = \frac{10\,\mathrm{nCi}}{4.331\text{E-}30} = 2.309\text{E+}30\,\mathrm{nCi} \tag{5-4}$$

The intake rates are given by dividing the respective intakes by 100 days. What would the intake be if the source material was ^{232}Th in equilibrium with its progeny? As with the acute intake:

$$\left[I_{\mathrm{th232}}\tilde{m}_{\mathrm{pbth232}}(365{,}100) + I_{\mathrm{ra228}}\tilde{m}_{\mathrm{pbra228}}(365{,}100) + I_{\mathrm{th228}}\tilde{m}_{\mathrm{pbth228}}(365{,}100)\right] = 10\,\mathrm{nCi} \tag{5-5}$$

Setting the intakes of ^{228}Ra and ^{228}Th equal to the intake of ^{232}Th and rearranging gives:

$$I_{\mathrm{th232}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{pbth232}}(365{,}100) + \tilde{m}_{\mathrm{pbra228}}(365{,}100) + \tilde{m}_{\mathrm{pbth228}}(365{,}100)} = 3.928\text{E+}02\,\mathrm{nCi} \tag{5-6}$$

The intakes of all the members of the ^{232}Th decay chain are equal to the intake of ^{232}Th.

Example 5-2

What would the intake be if the source material was ^{232}Th with the activity of the ^{228}Ra in the source material being one-half of the ^{232}Th activity and the activity of the ^{228}Th in the source material being one-quarter of the ^{232}Th activity?

$$I_{\mathrm{th232}} = \frac{10\,\mathrm{nCi}}{\tilde{m}_{\mathrm{pbth232}}(365{,}100) + 0.5\tilde{m}_{\mathrm{pbra228}}(365{,}100) + 0.25\tilde{m}_{\mathrm{pbth228}}(365{,}100)} = 1.218\text{E+}03\,\mathrm{nCi} \tag{5-7}$$

This means the inhalation intake consisted of 1,218 nCi of ^{232}Th, 1,218 ÷ 2 = 609 nCi of ^{228}Ra, and 1218 ÷ 4 = 305 nCi of ^{228}Th.

Example 5-3

What would the intake be if the ^{212}Pb and ^{232}Th were in secular equilibrium, exhibited shared kinetics, and no ^{220}Rn was lost from the body?

$$I_{\text{th232}} = \frac{10\,\text{nCi}}{\tilde{m}_{\text{th232}}(365{,}100)} = \frac{10\,\text{nCi}}{2.782\text{E-02}} = 3.595\text{E+02}\,\text{nCi} \qquad (5\text{-}8)$$

Note that the IRF in this equation is for the ^{232}Th because the ^{212}Pb is assumed to be present in a quantity equal to that of the ^{232}Th.

Example 5-4

What would the intake be if the source material was ^{232}Th with the activity of the ^{228}Ra in the source material being one-half of the ^{232}Th and there was a measured 10 nCi of ^{228}Ac in the chest 365 days after the start of a 100-day chronic intake?

$$\begin{aligned} I_{\text{th232}} &= \frac{10\,\text{nCi}}{\tilde{m}_{\text{acth232}}(365{,}100) + 0.5\tilde{m}_{\text{acra228}}(365{,}100)} \\ &= \frac{10\,\text{nCi}}{(2.732\text{E-03}) + 0.5(2.507\text{E-02})} \\ &= 6.549\text{E+02}\,\text{nCi} \end{aligned} \qquad (5\text{-}9)$$

This means the intake consisted of 655 nCi of ^{232}Th and 655 ÷ 2 = 328 nCi of ^{228}Ra.

5.1 URINE BIOASSAY

Example 5-5

What are the ^{232}Th and ^{228}Th intakes implied by 10 pCi of total thorium measured in the urine at 365 days after the start of a 100-day chronic intake? As with the acute intake version of this problem, the excretion function is:

$$\left[I_{\text{th232}}\tilde{m}_{\text{th232}}(365{,}100) + I_{\text{th232}}\tilde{m}_{\text{thth232}}(365{,}100) + I_{\text{th228}}\tilde{m}_{\text{th228}}(365{,}100)\right] = 10\,\text{pCi} \qquad (5\text{-}10)$$

Assuming single-separation thorium, this simplifies to:

$$I_{\text{th232}}\left[\tilde{m}_{\text{th232}}(365{,}100) + \tilde{m}_{\text{thth232}}(365{,}100) + 0.42\tilde{m}_{\text{th228}}(365{,}100)\right] = 10\,\text{pCi} \qquad (5\text{-}11)$$

Rearranging and solving this equation gives the ^{232}Th intake:

$$\begin{aligned} I_{\text{th232}} &= \frac{10\,\text{pCi}}{\tilde{m}_{\text{th232}}(365,100) + \tilde{m}_{\text{thth232}}(365,100) + 0.42\tilde{m}_{\text{th228}}(365,100)} \\ &= \frac{10\,\text{pCi}}{(2.896\text{E-07}) + (3.503\text{E-09}) + 0.42(2.129\text{E-07})} \\ &= 2.614\text{E+07}\,\text{pCi} \end{aligned} \qquad (5\text{-}12)$$

The ^{228}Th intake is:

$$I_{\text{th228}} = 0.42 I_{\text{th232}} = 1.098\text{E+07}\,\text{pCi} \qquad (5\text{-}13)$$

6.0 USING IMBA FOR EFFICIENCY CALCULATIONS

DCAL can be used to perform best-estimate dose reconstructions of thorium intakes based on bioassay data and the resulting organ doses. However, DCAL is not ideal for routine dose reconstructions because it is designed to be used in a batch mode and its output requires further processing with a custom code to obtain chronic intake burdens.

To facilitate efficiency calculations, ways are suggested here to adjust intakes and intake rates that are calculated with IMBA so that they will not underestimate those that are calculated with exact methods based on DCAL. A summary of the efficiency calculations is given in Attachment C. These adjustments can be used to perform efficiency calculations when an overestimate of dose is appropriate and a single measurement is being evaluated (which is typical for missed dose calculations). Efficiency methods using IMBA are not provided for ^{228}Ac chest counts[5], which should be evaluated with DCAL. IMBA cannot be used for best estimates of intake and dose, which require the use of DCAL.

7.0 USING IMBA FOR CHEST COUNTS

7.1 ACUTE INTAKES

Assume a mixture of 1 nCi of ^{232}Th and 1 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{212}Pb chest burden as a function of time after the acute intake is shown in Figure 7-1.

[5] The approximations given in Equations 7-3 and 7-4 that make efficiency calculations feasible for ^{212}Pb do not have valid counterparts for ^{228}Ac.

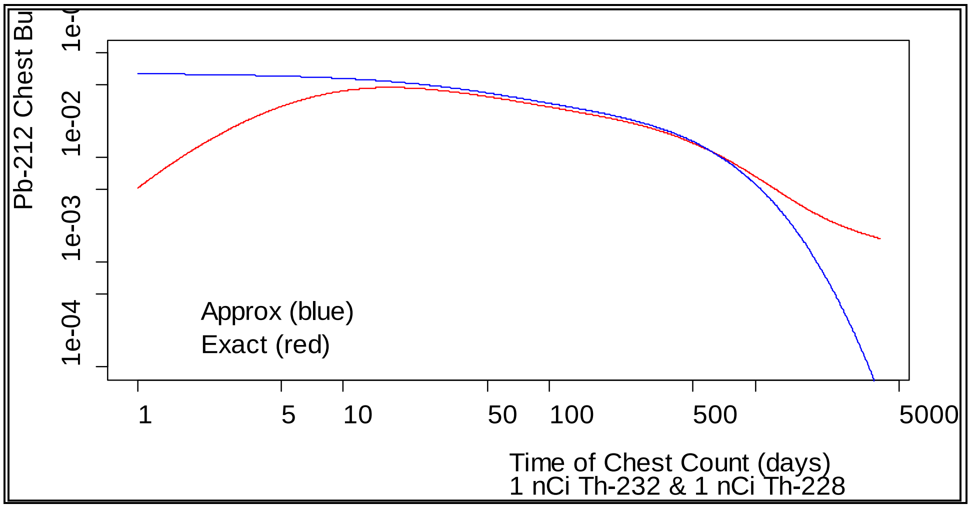

Figure 7-1. Lead-212 chest burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 1:1.

The exact chest burden q of ^{212}Pb at t days after an acute inhalation intake is given by:

$$q(t) = q_{\text{pbth232}}(t) + q_{\text{pbth228}}(t) \tag{7-1}$$

where q_{pbth232} is the chest burden of ^{212}Pb that grows in from the inhaled ^{232}Th and q_{pbth228} is the chest burden of ^{212}Pb that grows in from the inhaled ^{228}Th.

These exact burdens are calculated with DCAL, which accounts for independent kinetics of the thorium decay chain and the loss of ^{220}Rn. This relationship can be restated in terms of intakes and IRFs:

$$q(t) = I_{\text{th232}} m_{\text{pbth232}}(t) + I_{\text{th228}} m_{\text{pbth228}}(t) \tag{7-2}$$

Two approximations can be made:

1. The amount of ^{212}Pb present equals the amount of ^{228}Th present at all times after the intake:

$$m_{\text{pbth228}}(t) = m_{\text{th228}}(t) \tag{7-3}$$

2. There is negligible ingrowth of ^{212}Pb from the ^{232}Th component of the intake:

$$m_{\text{pbth232}}(t) = 0 \tag{7-4}$$

This gives the following approximation to q:

$$q'(t) = I_{\text{th228}} m_{\text{th228}}(t) \tag{7-5}$$

where m_{th228} is the ^{228}Th chest IRF at time t (which can be calculated with IMBA). As seen in the plot above, these approximations provide reasonably accurate estimates of the ^{212}Pb burden between approximately 10 and 1,000 days after the intake.

Example 7-1

For example, assume that a ^{212}Pb chest burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this thorium. Given a ^{228}Th:^{232}Th ratio of 1: 1, the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{1.5\,\text{nCi}}{m_{\text{pbth232}}(100) + m_{\text{pbth228}}(100)} \\ &= \frac{1.5\,\text{nCi}}{(4.640\text{E-05}) + (3.060\text{E-02})} \\ &= 4.895\text{E+01}\,\text{nCi} \end{aligned} \quad (7\text{-}6)$$

which translates into 48.95 nCi of ^{228}Th. These exact intakes (calculated with DCAL) can be checked by calculating the expected ^{212}Pb chest burden to determine if it equals the burden from which the intakes were calculated:

$$1.5\,\text{nCi} = (48.95\,\text{nCi})(4.64\text{E-05}) + (48.95\,\text{nCi})(0.0306) \quad (7\text{-}7)$$

With the approximate method we have a ^{228}Th intake of:

$$I = \frac{1.5\,\text{nCi}}{m_{\text{th228}}(100)} = \frac{1.5\,\text{nCi}}{0.0332} = 45.18\,\text{nCi}, \quad (7\text{-}8)$$

which translates into a 45.18 nCi intake of ^{232}Th. Note that in this example:

- For a given <u>intake</u> the exact method gives a lower <u>chest burden</u> than does the approximate method at t = 100 days (see Figure 7-1).

- However, for a given <u>chest burden</u> the exact method gives a larger <u>intake</u> than does the approximate method.

In practice dose reconstructors typically calculate intakes from chest burdens. Therefore, the plot in Figure 7-1 can be interpreted to mean that the approximate method will underestimate intakes at times before ~300 days after the intake (where the curves cross) and overestimate intakes after that day.

7.1.1 <u>Triple-Separated Thorium Mixture</u>

As noted in Section 3.0, triple-separated thorium has a ^{228}Th:^{232}Th ratio of 0.19:1. Assume a mixture of 1 nCi of ^{232}Th and 0.19 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{212}Pb chest burden as a function of time after the acute intake is shown in Figure 7-2.

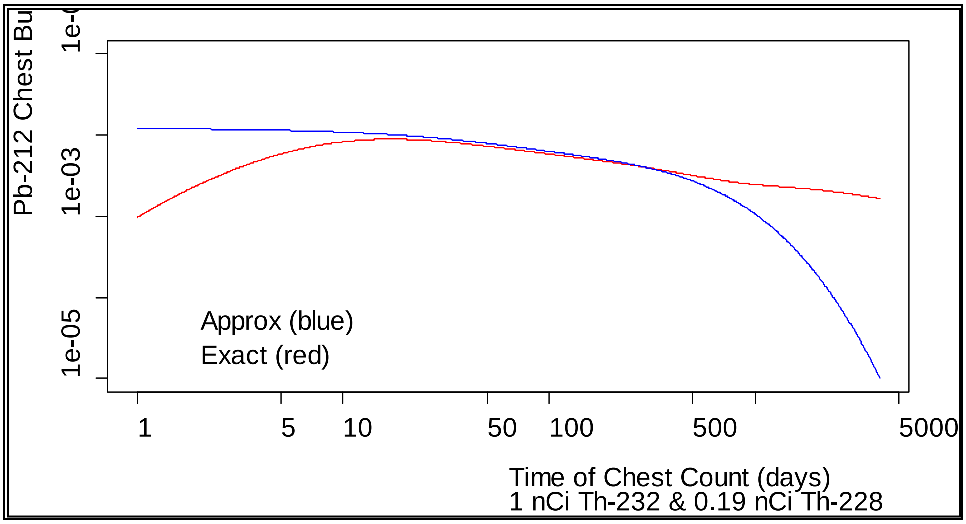

Figure 7-2. Lead-212 chest burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

Once again, the exact chest burden *q* of ^{212}Pb at *t* days after an acute inhalation intake is given by:

$$q(t) = I_{th232} m_{pbth232}(t) + I_{th228} m_{pbth228}(t) \tag{7-9}$$

and the approximation is:

$$q'(t) = I_{th228} m_{th228}(t) \tag{7-10}$$

Example 7-2

For example, assume that a ^{212}Pb chest burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this triple-separated Type S thorium. Given a ^{228}Th:^{232}Th ratio of 0.19, the exact intake (calculated with DCAL) of ^{232}Th is:

$$\begin{aligned} I_{th232} &= \frac{1.5\,\text{nCi}}{m_{pbth232}(100) + 0.19 m_{pbth228}(100)} \\ &= \frac{1.5\,\text{nCi}}{4.64\text{E-}05 + (0.19)(0.0306)} \\ &= 255.96\,\text{nCi} \end{aligned} \tag{7-11}$$

which translates into 0.19 × 255.96 nCi = 48.63 nCi of ^{228}Th. As a check, it is useful to show that:

$$1.5\,\text{nCi} = (255.96\,\text{nCi})(4.64\text{E-}05) + (48.63\,\text{nCi})(0.0306) \tag{7-12}$$

With the approximate method the intake of ^{228}Th is:

$$I_{th228} = \frac{1.5\,\text{nCi}}{m_{th228}(100)} = \frac{1.5\,\text{nCi}}{0.0332} = 45.18\,\text{nCi} \tag{7-13}$$

which gives 45.18 nCi ÷ 0.19 = 237.79 nCi of ^{232}Th.

The plot for Type M triple-separated thorium is shown in Figure 7-3. Other than the fact that there is faster clearance of the thorium from the chest, all of the discussion above is directly applicable to Type M material.

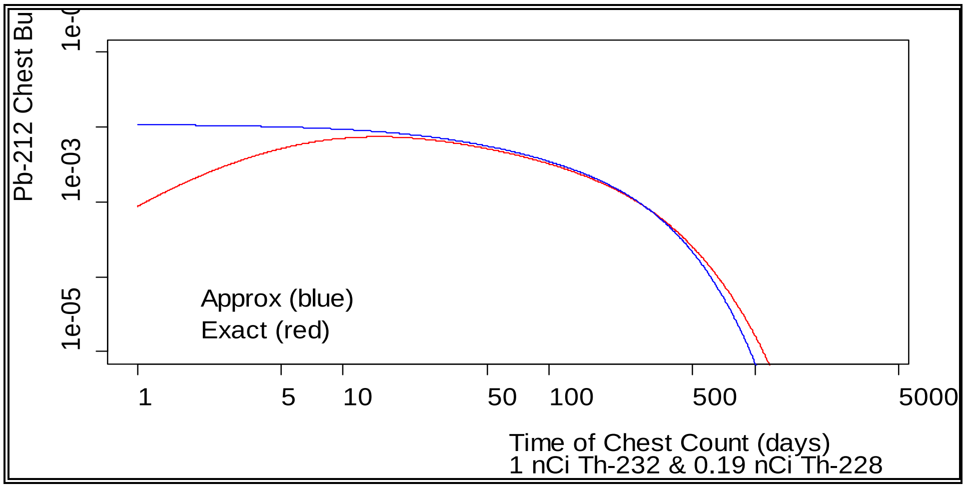

Figure 7-3. Lead-212 chest burden after an acute inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

7.1.2 <u>Adjustment of Thorium Intakes</u>

As shown in the plots above, for a given <u>thorium intake</u>, the approximate method will <u>overestimate</u> the ^{212}Pb chest burden for a length of time after the intake (~1 year for Type S material). Therefore, for a given <u>^{212}Pb chest burden</u>, the approximate method will <u>underestimate</u> the thorium intake for the same length of time. In Figures 7-4 and 7-5, an adjustment factor of 1/1.1 is applied to the approximate ^{212}Pb chest burdens to ensure that they do not overestimate the exact ^{212}Pb chest burdens at times greater than 30 days after intake.

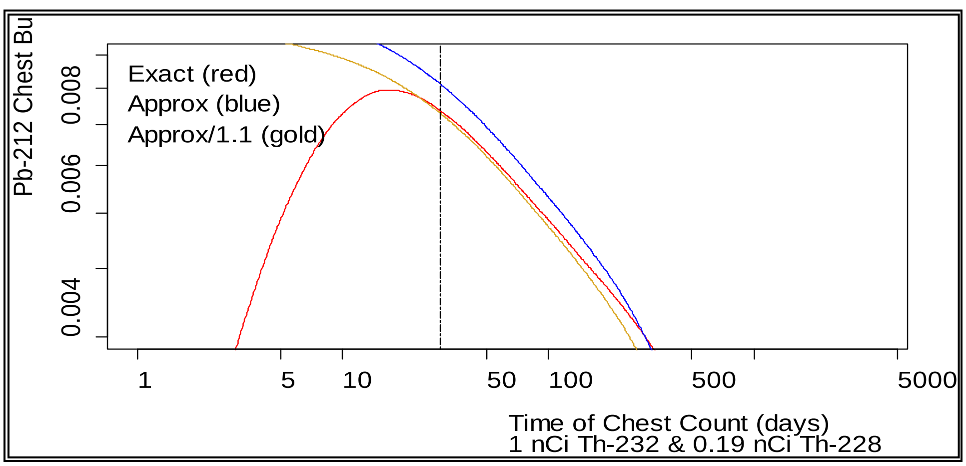

Figure 7-4. Lead-212 chest burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 with vertical dashed line at t = 30 days after intake.

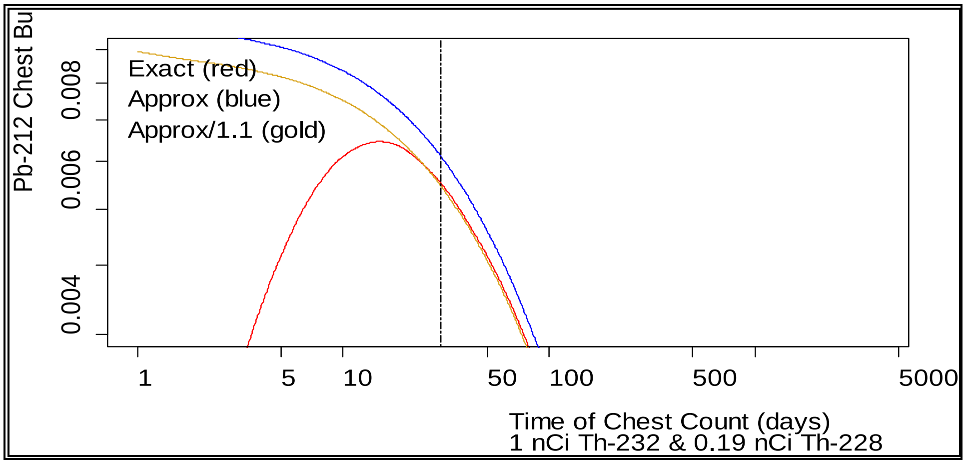

Figure 7-5. Lead-212 chest burden after an acute inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 with vertical dashed line at t = 30 days after intake.

When using the approximate method to calculate thorium intakes from ^{212}Pb chest burdens, the intake calculated with IMBA is multiplied by an adjustment factor of 1.1 to achieve the desired end of not underestimating the intake that would have been calculated using the exact method.

7.1.3 Guidance for Acute Intakes

Based on the discussion above, the following guidance is offered on how to use the approximate method to evaluate ^{212}Pb chest count data after acute inhalation intakes of Type M or S triple-separated thorium:

Assume a single measured ^{212}Pb *chest burden. Evaluate the chest burden with a* ^{228}*Th biokinetic model in IMBA. Multiply the calculated* ^{228}*Th intake by a factor of 1.1 and assign it as the intake of* ^{228}*Th. Divide this estimated* ^{228}*Th intake by the* ^{228}*Th:*^{232}*Th ratio of 0.19:1 to obtain the* ^{232}*Th intake. For* ^{212}*Pb chest burdens that are measured more than 30 days after an acute intake, these approximate intakes will not underestimate the intakes that would be calculated with exact methods.*

7.2 CHRONIC INTAKES

The plot in Figure 7-6 shows the ^{212}Pb chest burden as a function of time after a chronic intake of 1 nCi/d of ^{232}Th and 0.19 nCi/d of ^{228}Th (both being 5-µm AMAD Type S material). In other words, the time on the abscissa is the length of the time after the start of the chronic intake and the time that the chest burden is determined. The two curves cross at ~700 days.

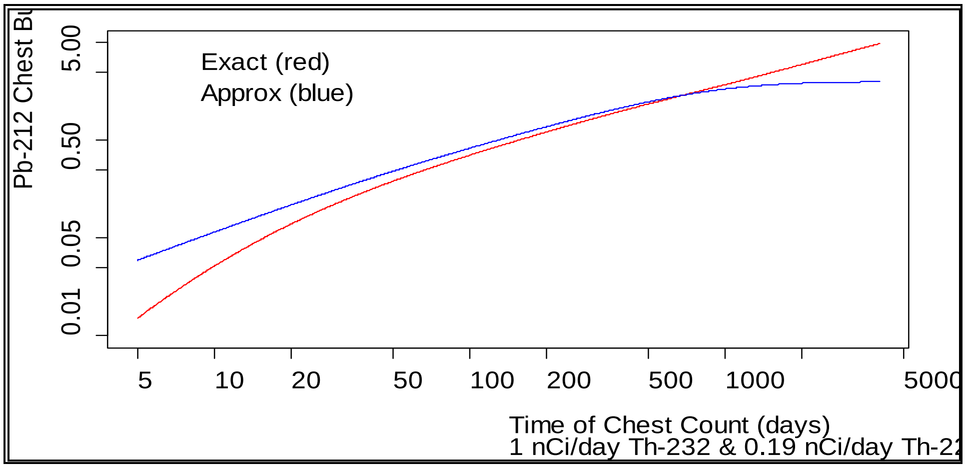

Figure 7-6. Lead-212 chest burden after a chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

The equations for chronic intakes are essentially the same as in the case of acute intakes except that the functions have an argument for the length of the constant chronic intake period. The exact chest burden q of ^{212}Pb at t days after the start of a chronic inhalation intake lasting t_c days is given by:

$$q(t,t_c) = q_{\text{pbth232}}(t,t_c) + q_{\text{pbth228}}(t,t_c) \qquad t \ge t_c \tag{7-14}$$

The relationship expressed in terms of intakes and IRFs is:

$$q(t,t_c) = I_{\text{th232}}\tilde{m}_{\text{pbth232}}(t,t_c) + I_{\text{th228}}\tilde{m}_{\text{pbth228}}(t,t_c) \qquad t \ge t_c \tag{7-15}$$

Applying the two approximations from Section 7.1 gives the following approximation to q:

$$q'(t,t_c) = I_{\text{th228}}\tilde{m}_{\text{th228}}(t,t_c) \tag{7-16}$$

Example 7-3

For example, assume that a ^{212}Pb chest burden of 1.5 nCi is observed at the end of a 365-day chronic inhalation intake of Type S triple-separated thorium. Given a ^{228}Th:^{232}Th ratio of 0.19:1, the total intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{1.5\,\text{nCi}}{\tilde{m}_{\text{pbth232}}(365,365) + 0.19\tilde{m}_{\text{pbth228}}(365,365)} \\ &= \frac{1.5\,\text{nCi}}{1.641\text{E-04} + (0.19)(0.02654)} \\ &= 288.1\,\text{nCi} \end{aligned} \tag{7-17}$$

which translates into 0.19 × 288.1 nCi = 54.74 nCi of ^{228}Th. This can be seen by rearranging the above equation:

$$1.5\,\text{nCi} = (288.1\,\text{nCi})(1.641\text{E-04}) + (54.74\,\text{nCi})(0.02654) \tag{7-18}$$

The intake rates are obtained by dividing the intakes by t_c = 365 days. With the approximate method the intake of ^{228}Th is:

$$I_{th228} = \frac{1.5\,\text{nCi}}{\tilde{m}_{th228}(365,365)} = \frac{1.5\,\text{nCi}}{(0.02980)} = 50.34\,\text{nCi} \tag{7-19}$$

which translates into 50.34 nCi ÷ 0.19 = 264.9 nCi of ^{232}Th.

The plot for Type M triple-separated thorium is shown in Figure 7-7. After a few hundred days the ^{212}Pb chest burden achieves a steady state condition with the approximate method giving a chest burden ~10% higher than the exact method.

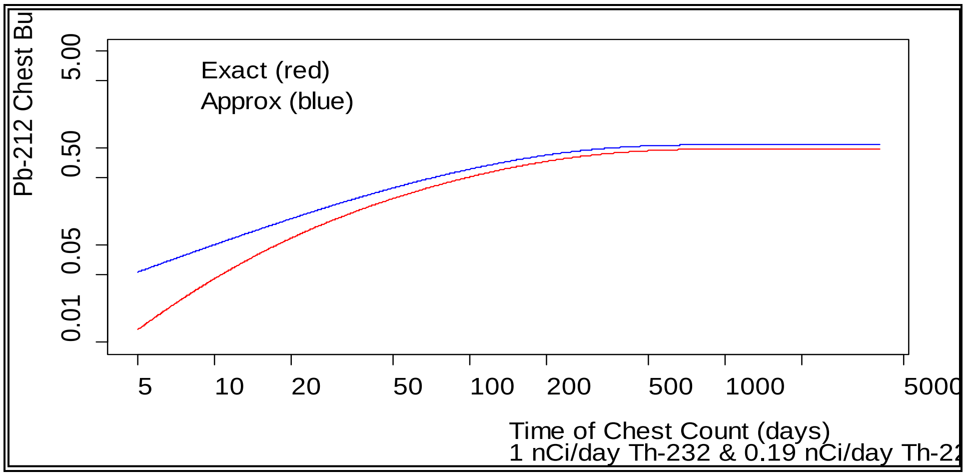

Figure 7-7. Lead-212 chest burden after a chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

7.2.1 Adjustment of Chronic Thorium Intakes

In Figures 7-8 to 7-13, the ^{212}Pb chest burdens at various times during and after 365 day, 1,000 day, and 5,000-day constant chronic intakes are presented. As with the acute intakes, the approximate ^{212}Pb chest burdens are adjusted by a factor of 1/1.1. This illustrates that intake rates that are calculated from ^{212}Pb chest counts with the approximate method can be adjusted by a factor of 1.1 to ensure that the intake rates do not underestimate the intake rates that are calculated with the exact method.

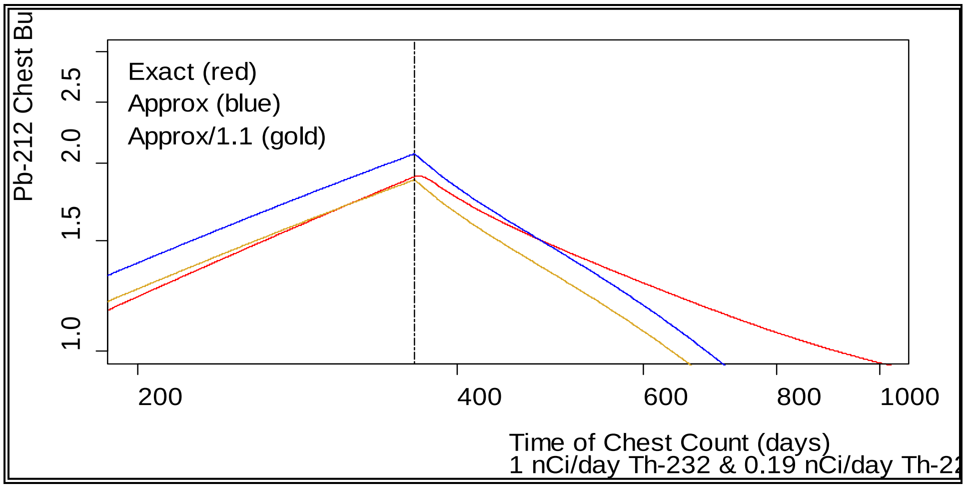

Figure 7-8. Lead-212 chest burden during and after a 365-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 365 days.

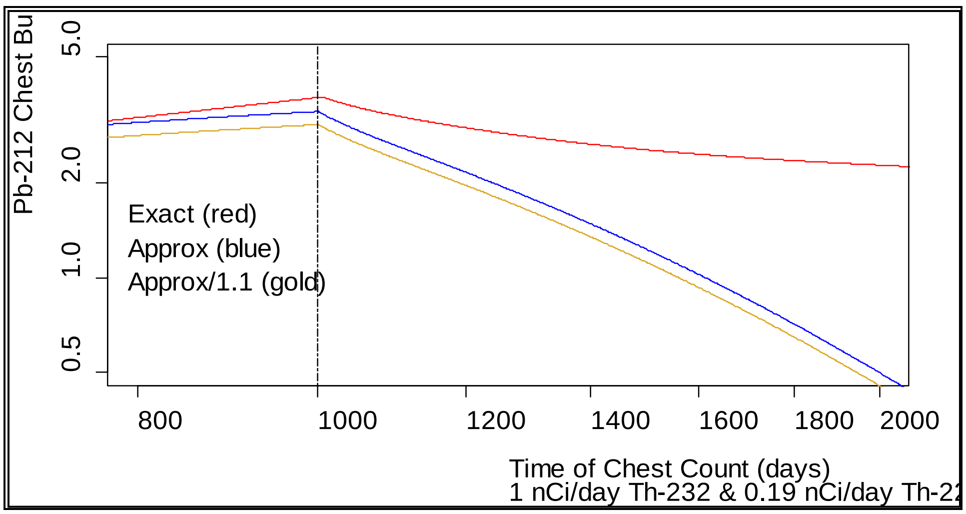

Figure 7-9. Lead-212 chest burden during and after a 1,000-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 1,000 days.

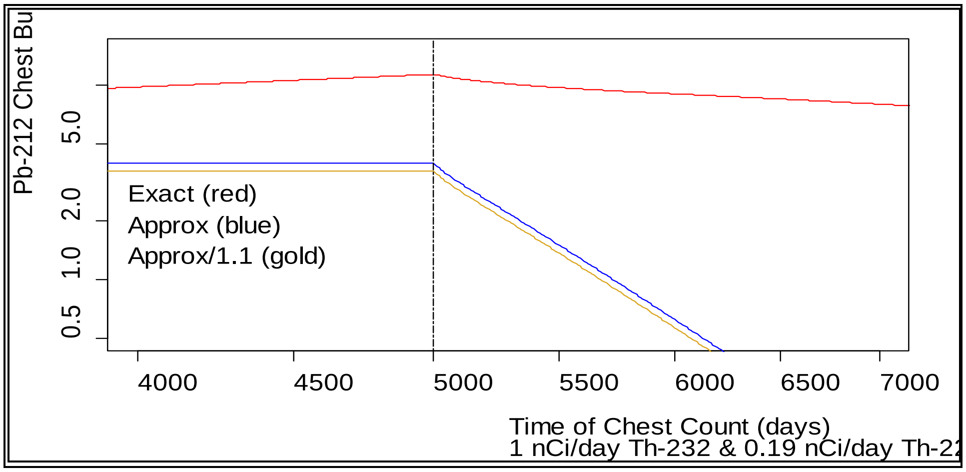

Figure 7-10. Lead-212 chest burden during and after a 5,000-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at t = 5,000 days.

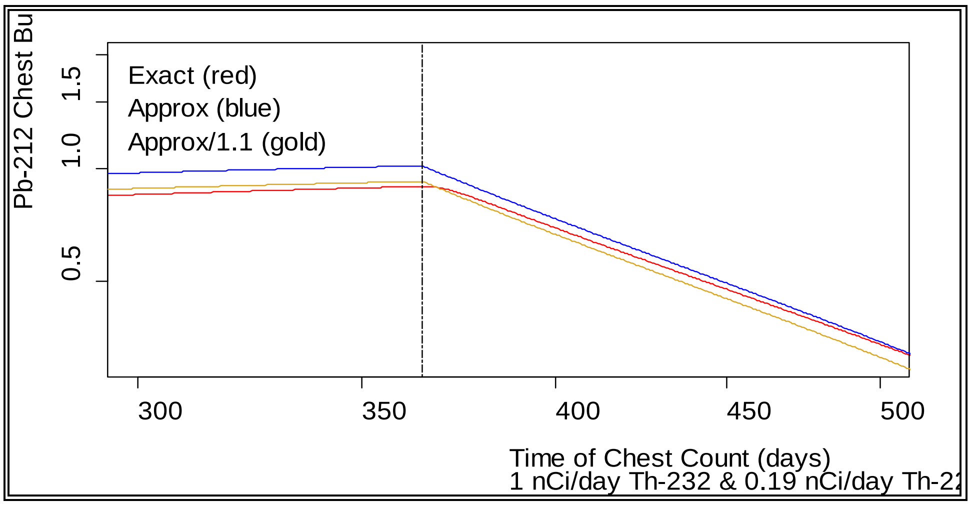

Figure 7-11. Lead-212 chest burden during and after a 365-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at t = 365 days.

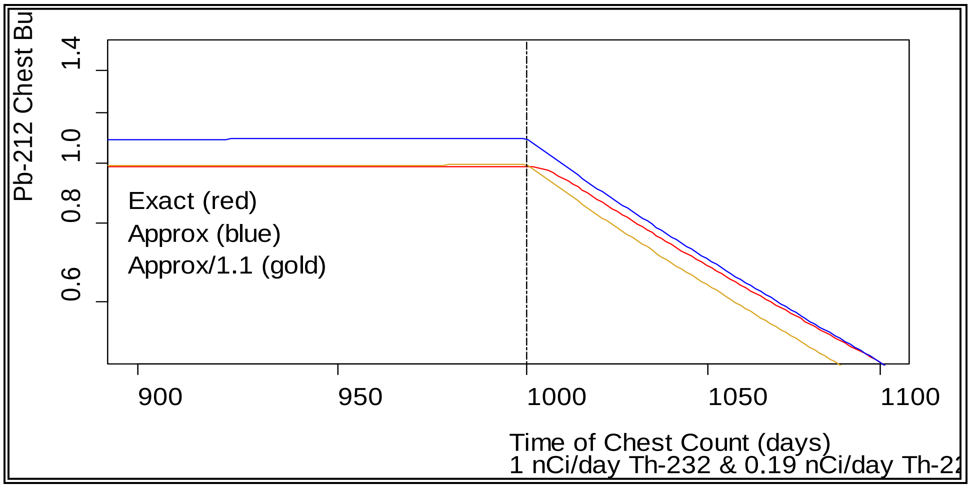

Figure 7-12. Lead-212 chest burden during and after a 1,000-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 1,000 days.

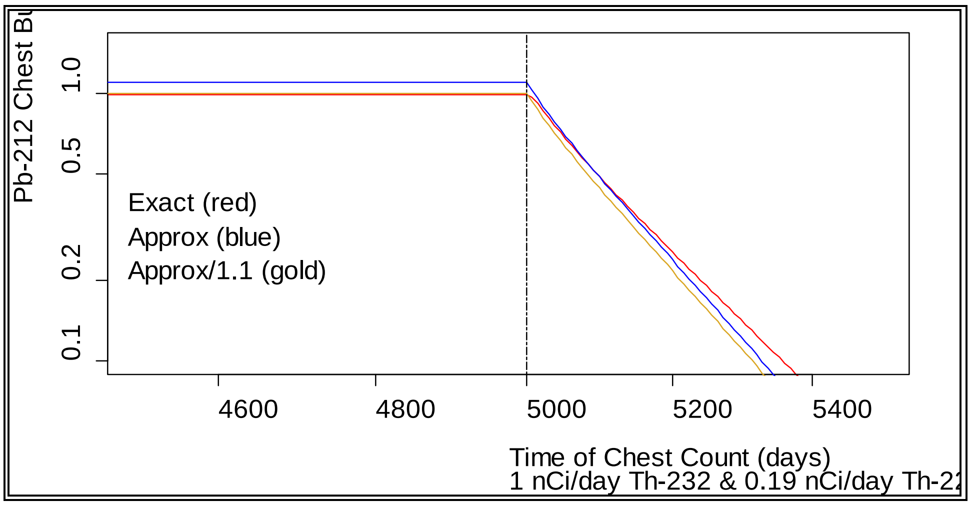

Figure 7-13. Lead-212 chest burden during and after a 5,000-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 5,000 days.

7.2.2 <u>Guidance for Chronic Intakes</u>

Based on the discussion above, the following guidance is offered on how to use the approximate method to evaluate ^{212}Pb chest count data after constant chronic inhalation intakes of triple-separated thorium:

Assume a single measured ^{212}Pb *chest burden. Evaluate the chest burden with a* ^{228}*Th biokinetic model in IMBA. Multiply the calculated* ^{228}*Th intake rate by a factor of 1.1 and assign it as the intake rate of* <u>^{228}*Th*</u>*. Divide this estimated* ^{228}*Th intake rate by the* ^{228}*Th:*^{232}*Th ratio of 0.19:1 to obtain the* <u>^{232}*Th*</u> *intake rate. For chronic intakes longer than 1 year these approximate intakes will not underestimate the intakes that would be calculated with exact methods.*

8.0 USING IMBA FOR WHOLE-BODY COUNTS

8.1 ACUTE INTAKES

Assume a mixture of 1 nCi of ^{232}Th and 1 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{212}Pb whole-body burden as a function of time after the acute intake is shown in Figure 8-1.

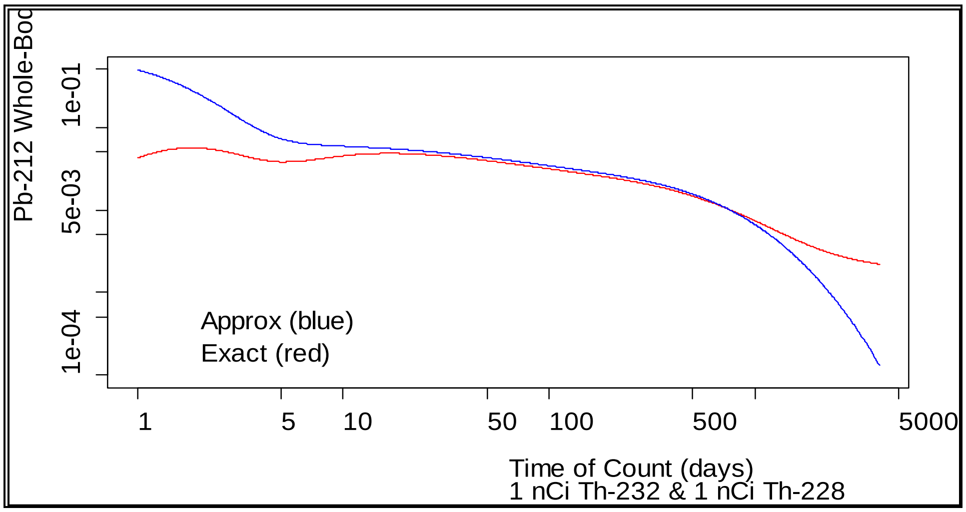

Figure 8-1. Lead-212 whole-body burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 1:1.

Analogous to the chest counts, the exact body burden *q* of ^{212}Pb at *t* days after an acute inhalation intake is given by:

$$q(t) = q_{\text{pbth232}}(t) + q_{\text{pbth228}}(t) \tag{8-1}$$

where q_{pbth232} is the whole-body burden of ^{212}Pb that grows in from the inhaled ^{232}Th and q_{pbth228} is the whole-body burden of ^{212}Pb that grows in from the inhaled ^{228}Th. The relationship expressed in terms of intakes and IRFs is:

$$q(t) = I_{\text{th232}} m_{\text{pbth232}}(t) + I_{\text{th228}} m_{\text{pbth228}}(t) \tag{8-2}$$

Applying the two approximations from Section 7.1 gives the following approximation to *q*:

$$q'(t) = I_{\text{th228}} m_{\text{th228}}(t) \tag{8-3}$$

As seen in the plot above, these approximations provide reasonably accurate estimates of the ^{212}Pb burden between approximately 10 and 1,000 days after the intake.

Example 8-1

For example, assume that a ^{212}Pb whole-body burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 1:1, the intake of ^{232}Th is:

$$\begin{aligned} I_{th232} &= \frac{1.5\,\text{nCi}}{m_{pbth232}(100) + m_{pbth228}(100)} \\ &= \frac{1.5\,\text{nCi}}{(4.750\text{E-05}) + (3.130\text{E-02})} \\ &= 4.785\text{E+01nCi} \end{aligned} \tag{8-4}$$

which translates into 47.85 nCi of ^{228}Th. These intakes can be checked by calculating the expected ^{212}Pb whole-body burden and seeing if it equals the burden from which the intakes were calculated:

$$1.5\,\text{nCi} = (4.785\text{E+01nCi})\left[(4.750\text{E-05}) + (3.130\text{E-02})\right] \tag{8-5}$$

With the approximate method we have a ^{228}Th intake of:

$$I_{th228} = \frac{1.5\,\text{nCi}}{m_{th228}(100)} = \frac{1.5\,\text{nCi}}{3.420\text{E-02}} = 4.386\text{E+1nCi} \tag{8-6}$$

which translates into a 43.86 nCi intake of ^{232}Th.

The plot in Figure 8-1 can be interpreted to mean that the approximate method will underestimate intakes at times before ~500 days after the intake (where the curves cross) and overestimate intakes after that day.

8.1.1 Triple-Separated Thorium Mixture

As noted in Section 3.0, triple-separated thorium has a ^{228}Th:^{232}Th ratio of 0.19:1. Assume a mixture of 1 nCi of ^{232}Th and 0.19 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{212}Pb whole-body burden as a function of time after the acute intake is shown in Figure 8-2.

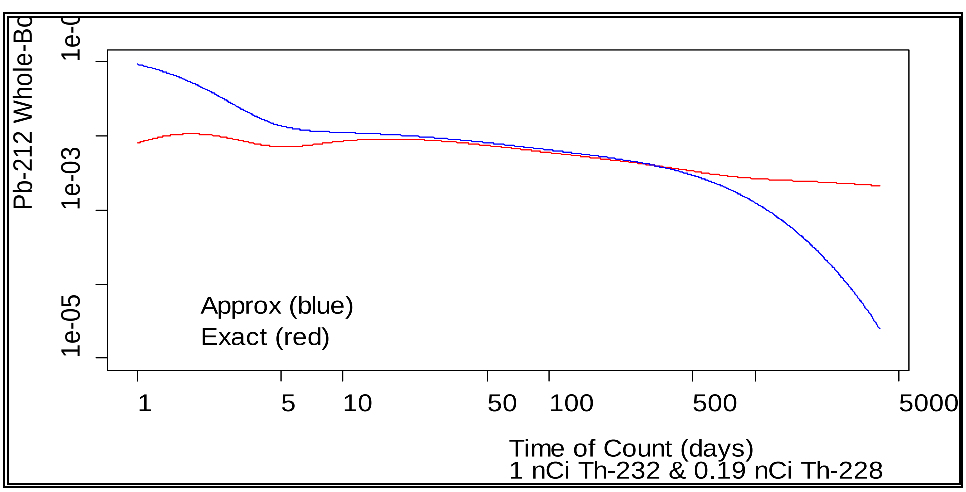

Figure 8-2. Lead-212 whole-body burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

As shown above, the ^{212}Pb body burden expressed in terms of intakes and IRFs is:

$$q(t) = I_{th232} m_{pbth232}(t) + I_{th228} m_{pbth228}(t) \tag{8-7}$$

Applying the two approximations from Section 7.1 gives the following approximation to q:

$$q'(t) = I_{th228} m_{th228}(t) \tag{8-8}$$

Example 8-2

For example, assume that a ^{212}Pb whole-body burden of 1.5 nCi is observed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 0.19:1, the intake of ^{232}Th is:

$$\begin{aligned} I_{th232} &= \frac{1.5\,\text{nCi}}{m_{pbth232}(100) + 0.19 m_{pbth228}(100)} \\ &= \frac{1.5\,\text{nCi}}{(4.130\text{E-}05) + (0.19)(3.900\text{E-}02)} \\ &= 2.013\text{E+}02\,\text{nCi} \end{aligned} \tag{8-9}$$

which translates into 0.19 × 201.3 nCi = 38.25 nCi of ^{228}Th. As a conceptual check, it is useful to show that:

$$1.5\,\text{nCi} = (201.3\,\text{nCi})(4.130\text{E-}05) + (38.25)(3.900\text{E-}02) \tag{8-10}$$

With the approximate method the intake of ^{228}Th is:

$$I_{th228} = \frac{1.5\,\text{nCi}}{m_{th228}(100)} = \frac{1.5\,\text{nCi}}{3.420\text{E-}02} = 4.386\text{E+}01\,\text{nCi} \tag{8-11}$$

which translates into 43.86 nCi ÷ 0.19 = 230.8 nCi of ^{232}Th.

The plot for Type M triple-separated thorium is shown in Figure 8-3. Other than the fact that there is faster clearance of the thorium from the chest, all of the discussion above is directly applicable to Type M material.

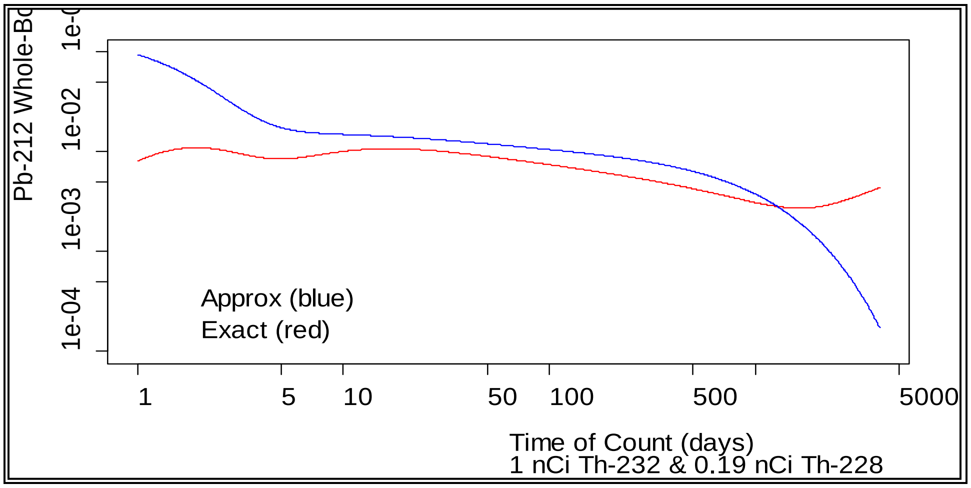

Figure 8-3. Lead-212 whole-body burden after an acute inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

8.1.2 Adjustment of Thorium Intakes

As shown in Figures 8-1 to 8-3, for a given thorium intake, the approximate method will overestimate the ^{212}Pb whole-body burden for a length of time after the intake (~2 years for Type S material). Therefore, for a given ^{212}Pb whole-body burden, the approximate method will underestimate the thorium intake for the same length of time. In Figures 8-4 and 8-5, an adjustment factors of 1/1.2 (Type S) and 1/1.5 (Type M) are applied to the approximate ^{212}Pb whole-body burdens to ensure that they do not overestimate the exact ^{212}Pb whole-body burdens at times greater than 30 days after intake.

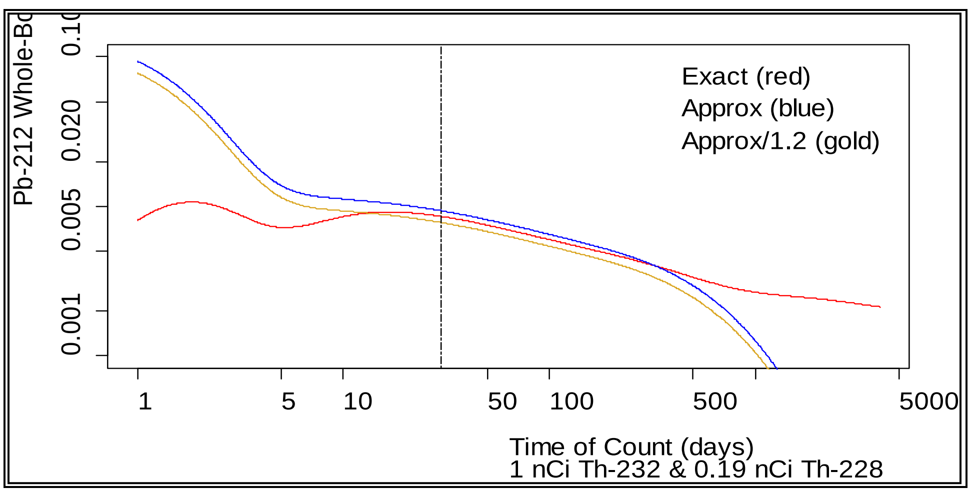

Figure 8-4. Lead-212 whole-body burden after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 with vertical dashed line at t = 30 days after intake.

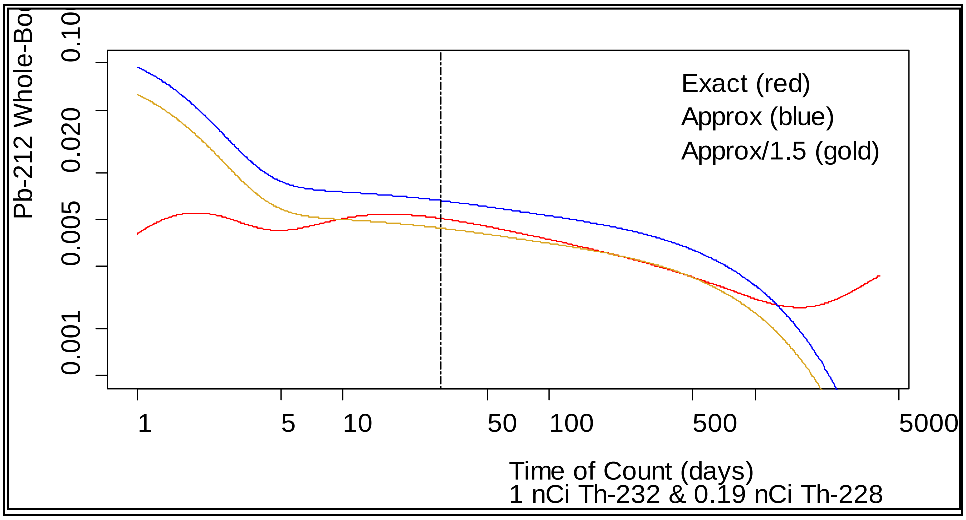

Figure 8-5. Lead-212 whole-body burden after an acute inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 with vertical dashed line at *t* = 30 days after intake.

When using the approximate method to calculate thorium intakes from ^{212}Pb whole-body burdens, the intake is multiplied by the appropriate adjustment factor to achieve the desired end of not underestimating the intake that would have been calculated using the exact method.

8.1.3 Guidance for Acute Intakes

Based on the discussion above, the following guidance is offered on how to use the approximate method to evaluate ^{212}Pb whole-body count data after acute inhalation intakes of Type M or S thorium:

Assume a single measured ^{212}Pb *whole-body burden. Evaluate the whole-body burden with a Type M* ^{228}Th *biokinetic model in IMBA. Multiply the calculated* ^{228}Th *intake by a factor of 1.5 and assign it as the intake of* ^{228}Th*. Divide this estimated* ^{228}Th *intake by the* ^{228}Th:^{232}*Th ratio of 0.19:1 to obtain the* ^{232}*Th intake. For* ^{212}Pb *whole-body burdens that were measured more than 30 days after an acute intake, these approximate intakes will not underestimate the Type M intakes that would be calculated with exact methods. For Type S thorium use a factor of 1.2 instead of 1.5.*

8.2 CHRONIC INTAKES

The plot in Figure 8-6 shows the ^{212}Pb whole-body burden as a function of time after a chronic intake of 1 nCi/d of ^{232}Th and 0.19 nCi/d of ^{228}Th (both being 5-µm AMAD Type S material). In other words, the time on the abscissa is the length of the time after the start of the chronic intake and the time that the whole-body burden is determined.

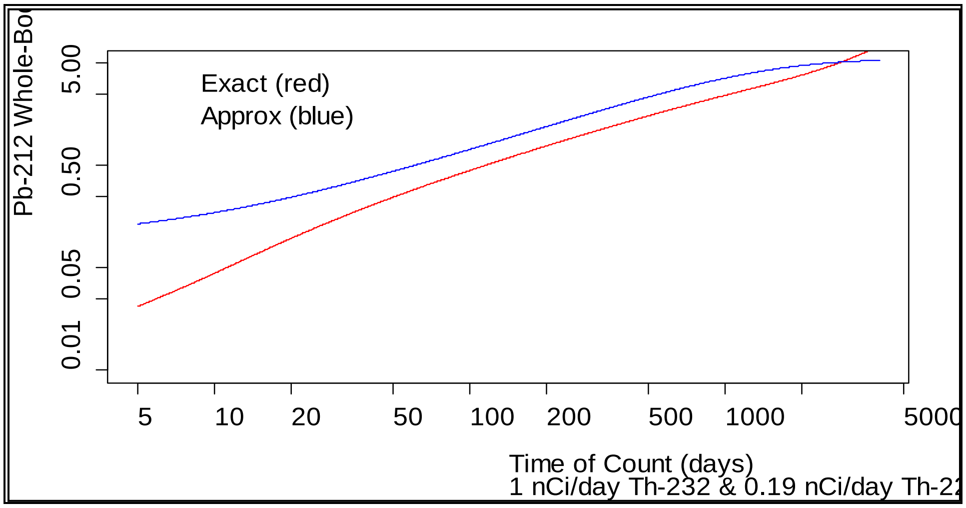

Figure 8-6. Lead-212 whole-body burden after a chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

The equations for chronic intakes are essentially the same as in the case of acute intakes except that the functions have an argument for the length of the constant chronic intake period. The exact whole-body burden q of ^{212}Pb at t days after the start of a chronic inhalation intake over t_c days is given by:

$$q(t,t_c) = q_{\text{pbth232}}(t,t_c) + 0.19 q_{\text{pbth228}}(t,t_c) \qquad t \geq t_c \tag{8-12}$$

Applying the two approximations from Section 7.1 gives the following approximation to q:

$$q'(t,t_c) = q_{\text{th228}}(t,t_c) \tag{8-13}$$

Example 8-3

For example, assume that a ^{212}Pb whole-body burden of 1.5 nCi is observed at the end of a 365-day chronic inhalation intake of Type S triple-separated thorium. The exact total intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{1.5\,\text{nCi}}{\tilde{m}_{\text{pbth232}}(365,365) + 0.19\tilde{m}_{\text{pbth228}}(365,365)} \\ &= \frac{1.5\,\text{nCi}}{(1.681\text{E-04}) + (0.19)(2.767\text{E-02})} \\ &= 2.765\text{E+02}\,\text{nCi} \end{aligned} \tag{8-14}$$

which translates into 0.19 × 276.7 nCi = 52.53 nCi of ^{228}Th. This can be seen by rearranging the above equation:

$$1.5\,\text{nCi} = (276.7\text{nCi})(1.681\text{E-04}) + (52.53\,\text{nCi})(2.767\text{E-02}) \tag{8-15}$$

The intake rates are obtained by dividing the intakes by t_c = 365 days. With the approximate method the intake of ^{228}Th is:

$$I_{\text{th228}} = \frac{1.5\,\text{nCi}}{\tilde{m}_{\text{th228}}(365,365)} = \frac{1.5\,\text{nCi}}{(3.378\text{E-02})} = 4.440\text{E+01}\text{nCi} \tag{8-16}$$

which gives 44.40 nCi ÷ 0.19 = 233.7 nCi of ^{232}Th. The plot for Type M triple-separated thorium is shown in Figure 8-7.

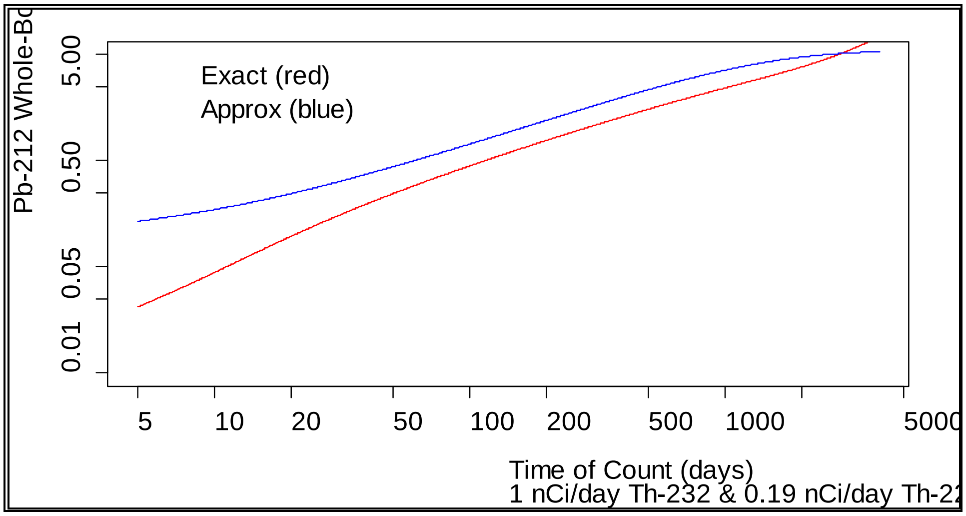

Figure 8-7. Lead-212 whole-body burden after a chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

8.2.1 Adjustment of Chronic Thorium Intakes

In Figures 8-8 to 8-13, the ^{212}Pb whole-body burdens at various times during and after 365-, 1,000-, and 5,000-day constant chronic intakes are presented. As with the acute intakes, the approximate ^{212}Pb whole-body burdens are adjusted by a factor of 1/1.2 for Type S and 1/1.5 for Type M. This illustrates that intake rates that are calculated from ^{212}Pb whole-body counts with the approximate method can be adjusted by the appropriate factor to ensure that the intake rates do not underestimate the intake rates that would be calculated with the exact method.

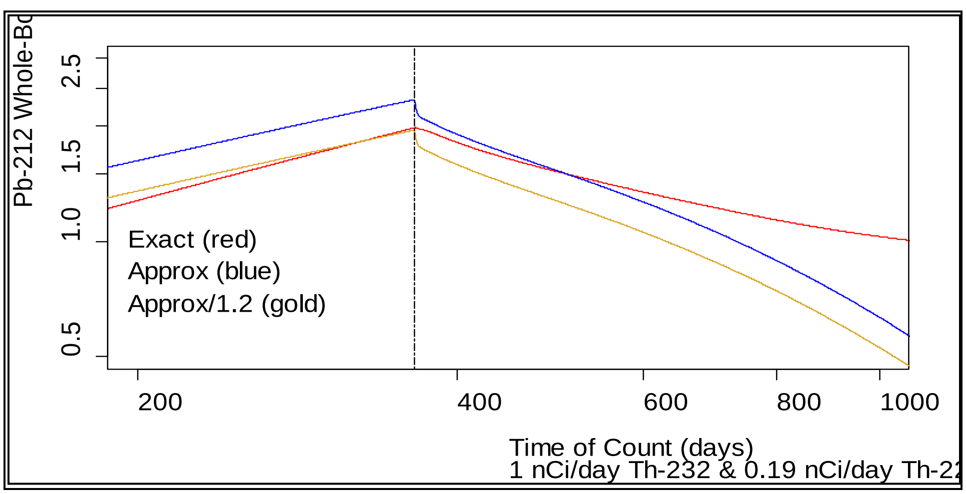

Figure 8-8. Lead-212 whole-body burden during and after a 365-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at t = 365 days.

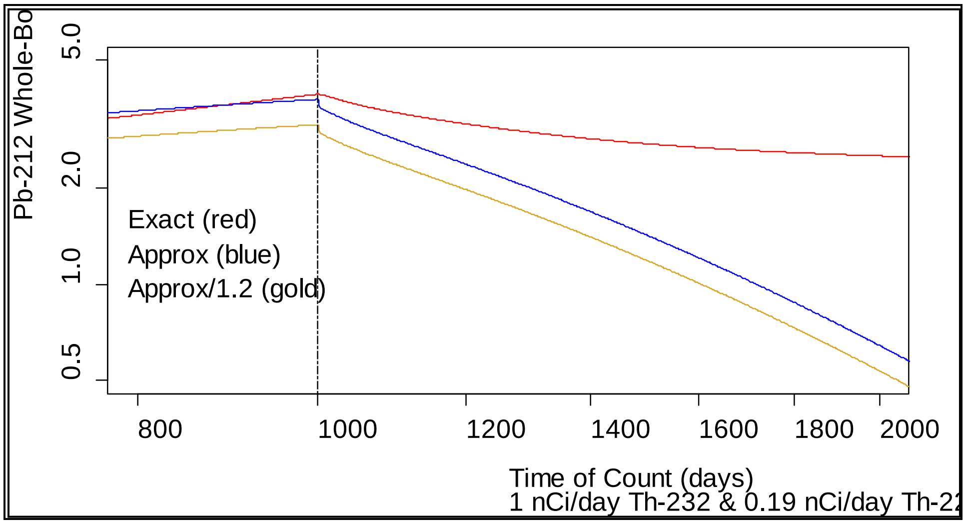

Figure 8-9. Lead-212 whole-body burden during and after a 1,000-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 1,000 days.

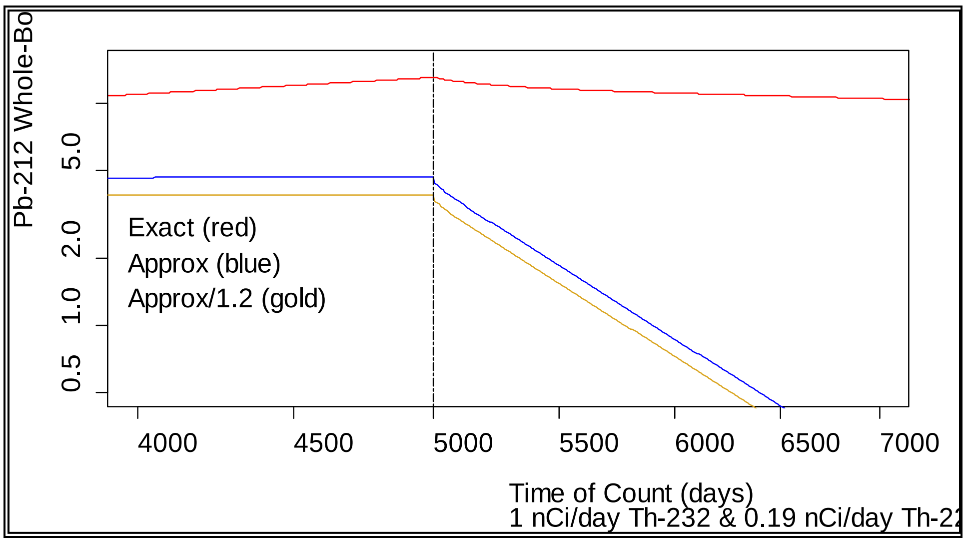

Figure 8-10. Lead-212 whole-body burden during and after a 5,000-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 5,000 days.

8.2.2 Guidance for Chronic Intakes

Based on the discussion above, the following guidance is offered on how to use the approximate method to evaluate ^{212}Pb whole-body count data after constant chronic inhalation intakes of triple-separated thorium:

Assume a single measured ^{212}Pb *whole-body burden. Evaluate the whole-body burden with a Type M* ^{228}*Th biokinetic model in IMBA. Multiply the calculated* ^{228}*Th intake rate by a factor of 1.5 and assign it as the intake rate of* ^{228}*Th. Divide this estimated* ^{228}*Th intake rate by the* ^{228}*Th:*^{232}*Th ratio of 0.19:1 to obtain the* ^{232}*Th intake rate. For chronic intakes longer than 1 year these approximate intakes will not underestimate the Type M intakes that would be calculated with exact methods. For Type S thorium use a factor of 1.2 instead of 1.5.*

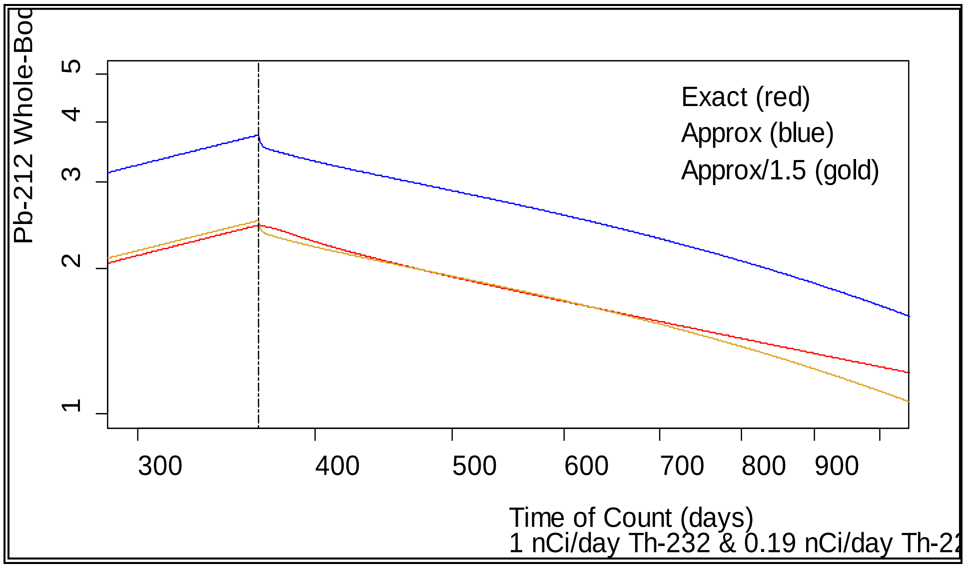

Figure 8-11. Lead-212 whole-body burden during and after a 365-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 365 days.

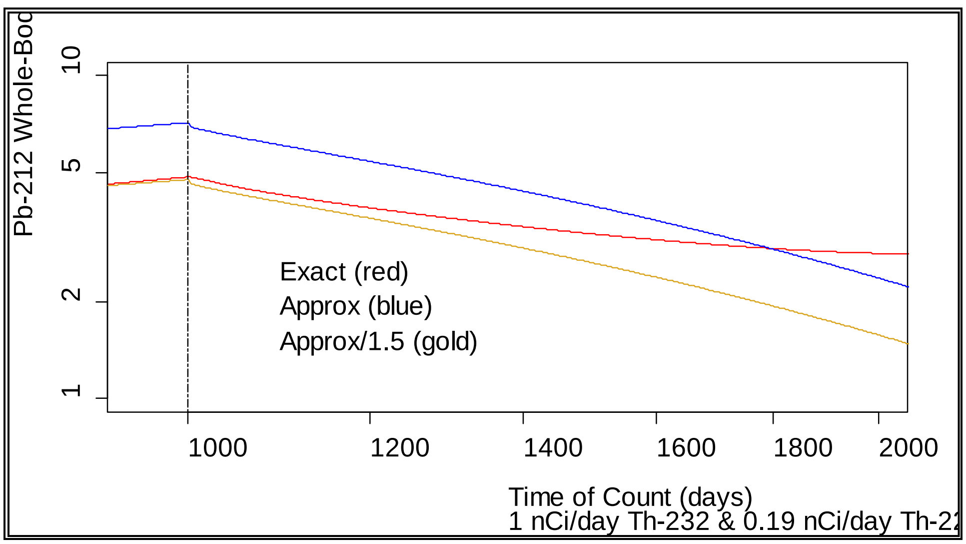

Figure 8-12. Lead-212 whole-body burden during and after a 1,000-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 1,000 days.

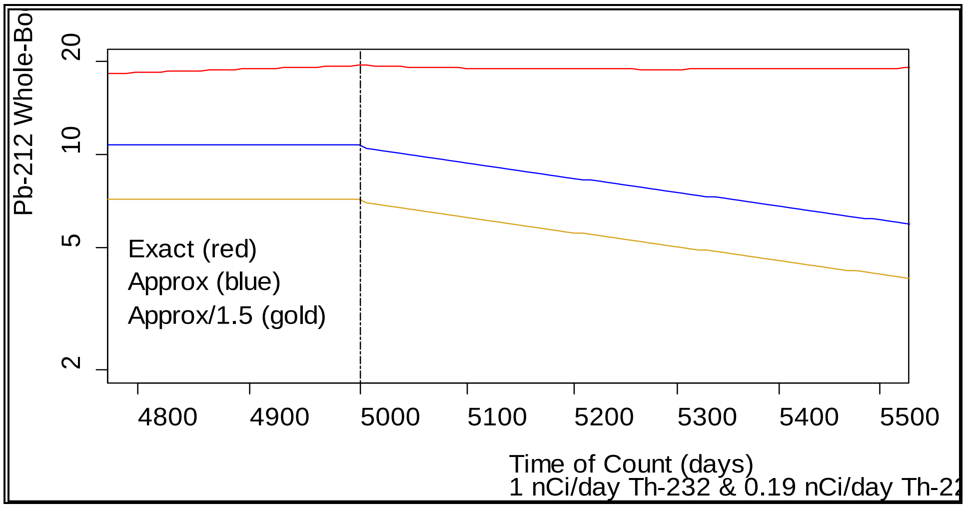

Figure 8-13. Lead-212 whole-body burden during and after a 5,000-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The vertical dashed line is at *t* = 5,000 days.

9.0 USING IMBA FOR TOTAL THORIUM IN URINE

This section discusses methods for adjustment of intakes and intake rates of ^{232}Th and ^{228}Th that are calculated with IMBA from total thorium (^{232}Th + ^{228}Th) measurements of urine samples so that the intakes and intake rates will not underestimate those that would be calculated with exact methods (i.e., using DCAL). These adjustments can be used when an overestimate of dose is appropriate. Best estimates of dose require the use of DCAL.

9.1 ACUTE INTAKES

Assume a mixture of 1 nCi of ^{232}Th and 1 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The total thorium (henceforth referred to simply as "thorium") in 24-hour incremental urine samples as a function of time after the acute intake is shown in Figure 9-1.

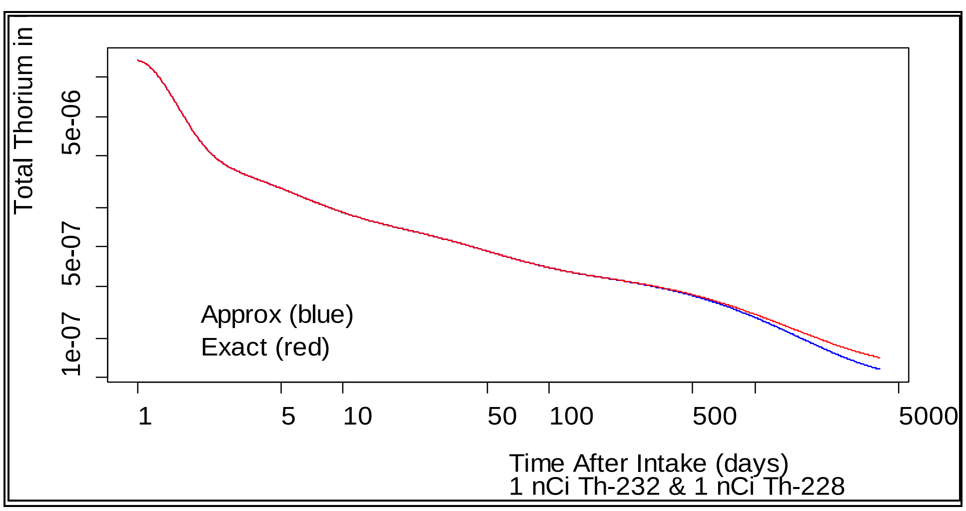

Figure 9-1. Thorium in 24-hour incremental urine samples after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 1:1.

The exact content q of thorium in the urine at t days after an acute inhalation intake is given by:

$$q(t) = q_{\text{th232}}(t) + q_{\text{thth232}}(t) + q_{\text{th228}}(t) \tag{9-1}$$

where q_{th232} is the amount of ^{232}Th in the sample, q_{thth232} is the amount of ^{228}Th in the sample that grows in from the inhaled ^{232}Th, and q_{th228} is the amount of ^{228}Th in the sample from the inhaled ^{228}Th. These exact contents are calculated with DCAL, which accounts for independent kinetics of the thorium decay chain. The red excretion curve in Figure 9-1 was calculated using the exact method. An approximation that can be made here is that there is negligible ingrowth of ^{228}Th from the ^{232}Th component of the intake. That is:

$$q_{\text{thth232}}(t) = 0 \qquad \{\textbf{Approximation A}\} \tag{9-2}$$

This gives the following approximation to q:

$$q'(t) = q_{\text{th232}}(t) + q_{\text{th228}}(t) \tag{9-3}$$

where q_{th232} is the ^{232}Th urine content and q_{th228} is the ^{228}Th urine contents at time t, both of which can be calculated with IMBA. The blue excretion curve in Figure 9-1 was calculated using the approximate method. As seen in Figure 9-1, this approximation provides reasonably accurate estimates of the thorium urine content for a couple of years after the intake. At later times the approximate method underestimates the urinary excretion rate.

Example 9-1

For example, assume that 0.0015 nCi of thorium is observed in a 24-hour urine sample completed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 1:1, the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{m_{\text{th232}}(100) + m_{\text{thth232}}(100) + m_{\text{th228}}(100)} \\ &= \frac{0.0015\,\text{nCi}}{3.65\text{E-07} + 4.64\text{E-10} + 3.31\text{E-07}} \\ &= 2{,}154\,\text{nCi} \end{aligned} \tag{9-4}$$

which translates into 2,154 nCi of ^{228}Th. These intakes can be checked by calculating the expected thorium urine content and determining if it equals the content from which the intakes were calculated:

$$0.0015\,\text{nCi} = I_{\text{th232}} m_{\text{th232}}(100) + I_{\text{th232}} m_{\text{thth232}}(100) + I_{\text{th228}} m_{\text{th228}}(100) \tag{9-5}$$

$$0.0015\,\text{nCi} = (2{,}154\,\text{nCi})(3.65\text{E-07}) + (2{,}154\,\text{nCi})(4.64\text{E-10}) + (2{,}154\,\text{nCi})(3.31\text{E-07}) \tag{9-6}$$

With the approximate method we have a ^{232}Th intake of:

$$
\begin{aligned}
I_{th232} &= \frac{0.0015\,\text{nCi}}{m_{th232}(100) + m_{th228}(100)} \\
&= \frac{0.0015\,\text{nCi}}{3.65\text{E-}07 + 3.31\text{E-}07} \qquad (9\text{-}7) \\
&= 2{,}155\,\text{nCi}
\end{aligned}
$$

which translates into a 2,155 nCi intake of ^{228}Th. From the equations above it should be evident that, for a given quantity of thorium in the urine, the approximate method will always give an intake that is greater than or equal to the intake from the exact method (this is reflected in Figure 9-1). Further, this is true regardless of the ^{228}Th:^{232}Th ratio, dissolution type (M or S), or exposure pattern (acute or chronic).

9.1.1 Triple-Separated Thorium Mixture

As noted in Section 3.0, triple-separated thorium has a ^{228}Th:^{232}Th ratio of 0.19:1. Assume a mixture of 1 nCi of ^{232}Th and 0.19 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The thorium urine content as a function of time after the acute intake is shown in Figure 9-2.

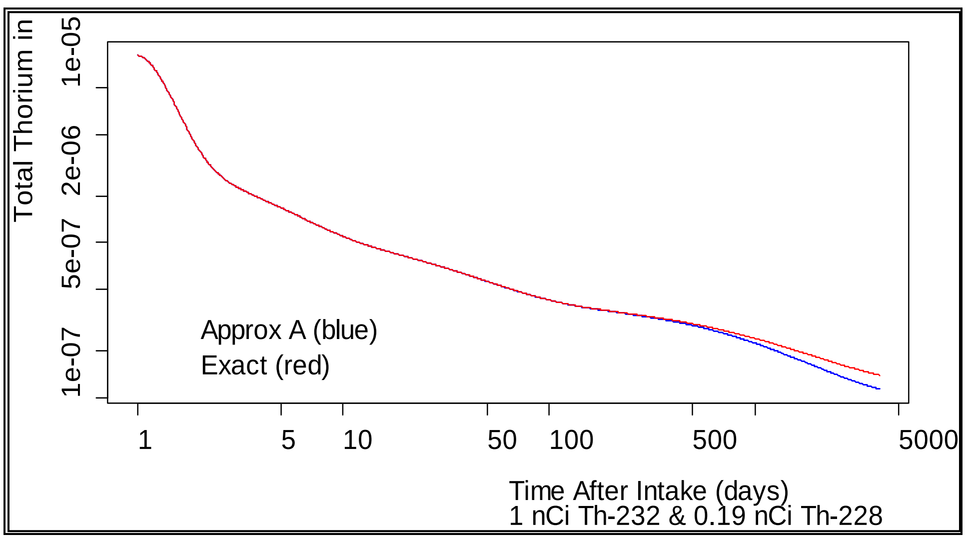

Figure 9-2. Thorium urine content after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

Example 9-2

For example, assume that 0.0015 nCi of thorium is observed in a 24-hour urine sample completed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 0.19:1, the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{m_{\text{th232}}(100) + m_{\text{thth232}}(100) + 0.19 m_{\text{th228}}(100)} \\ &= \frac{0.0015\,\text{nCi}}{3.65\text{E-07} + 4.64\text{E-10} + (0.19)(3.31\text{E-07})} \\ &= 3{,}502\,\text{nCi} \end{aligned} \tag{9-8}$$

which translates into 665 nCi of ^{228}Th. These intakes can be checked by calculating the expected thorium urine content and seeing if it equals the content from which the intakes were calculated:

$$\begin{aligned} 0.0015\,\text{nCi} = {} & (3{,}502\,\text{nCi})(3.65\text{E-07}) + (3{,}502\,\text{nCi})(4.64\text{E-10}) \\ & + (0.19)(3{,}502\,\text{nCi})(3.31\text{E-07}) \end{aligned} \tag{9-9}$$

With the approximate method we have a ^{232}Th intake of:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{m_{\text{th232}}(100) + 0.19 m_{\text{th228}}(100)} \\ &= \frac{0.0015\,\text{nCi}}{3.65\text{E-07} + (0.19)(3.31\text{E-07})} \\ &= 3{,}506\,\text{nCi} \end{aligned} \tag{9-10}$$

which translates into a 666 nCi intake of ^{228}Th.

9.1.2 An Additional Approximation

The approximation above will provide an estimate of the intake that will not be less than the intake that would be calculated with the exact method regardless of the dissolution type or exposure pattern. However, in practice this approximation is cumbersome to use in IMBA because it requires calculation of intakes of two different radionuclides (^{232}Th and ^{228}Th), a task that requires two computational runs. An additional simplifying approximation that can be used with triple-separated thorium is to use the ^{232}Th urinary excretion function in place of the ^{228}Th function:

$$q_{\text{th228}}(t) = q_{\text{th232}}(t) \qquad \{\textbf{Approximation B}\} \tag{9-11}$$

which gives:

$$q''(t) = q_{\text{th232}}(t) + 0.19 q_{\text{th232}}(t) \tag{9-12}$$

This approximation is shown in Figure 9-3 as the gold curve, which partially obscures the exact (red) curve. Applying Approximations A and B gives a ^{232}Th intake of:

$$I_{\text{th232}} = \frac{0.0015\,\text{nCi}}{m_{\text{th232}}(100) + 0.19 m_{\text{th232}}(100)} = \frac{0.0015\,\text{nCi}}{1.19 m_{\text{th232}}(100)} \tag{9-13}$$

$$I_{th232} = \frac{0.0015\,\text{nCi}}{3.65\text{E-07} + (0.19)(3.65\text{E-07})} = \frac{0.0015\,\text{nCi}}{(1.19)(3.65\text{E-07})} = 3{,}453\,\text{nCi} \tag{9-14}$$

which translates into a 656-nCi intake of ^{228}Th. These approximations provide intake estimates for Type S material that are within ±5% of the exact intake for the periods studied here (i.e., less than 4,000 days).

As shown in Figure 9-4, there is a maximum nonconservative discrepancy on the order of 12% when Approximations A and B are applied to Type M thorium. To adjust for these underestimates, ^{232}Th intakes that are calculated with Approximations A and B are multiplied by a factor of 1.15. However, the ratio of 1.15:1.19 can be rounded up to 1, a conservative approximation that allows us to simplify the guidance even further:

$$\left(\frac{1.15}{1.19}\right) I_{\text{th232}} = I_{\text{th232}} \qquad \{\textbf{Approximation C}\} \tag{9-15}$$

9.1.3 <u>Guidance for Acute Intakes</u>

Based on the discussion above, the following guidance could be offered on how to use the approximate method to evaluate thorium urine bioassay measurements after acute inhalation intakes of Type M or S thorium:

Assume a single measured thorium urine bioassay result. Evaluate the result with a ^{232}Th biokinetic model in IMBA to obtain an estimate of the ^{232}Th intake. Multiply this estimate of the ^{232}Th intake by the ^{228}Th:^{232}Th ratio of 0.19:1 to obtain the estimate of the ^{228}Th intake. These approximate intakes will not underestimate the intakes that would be calculated with exact methods.

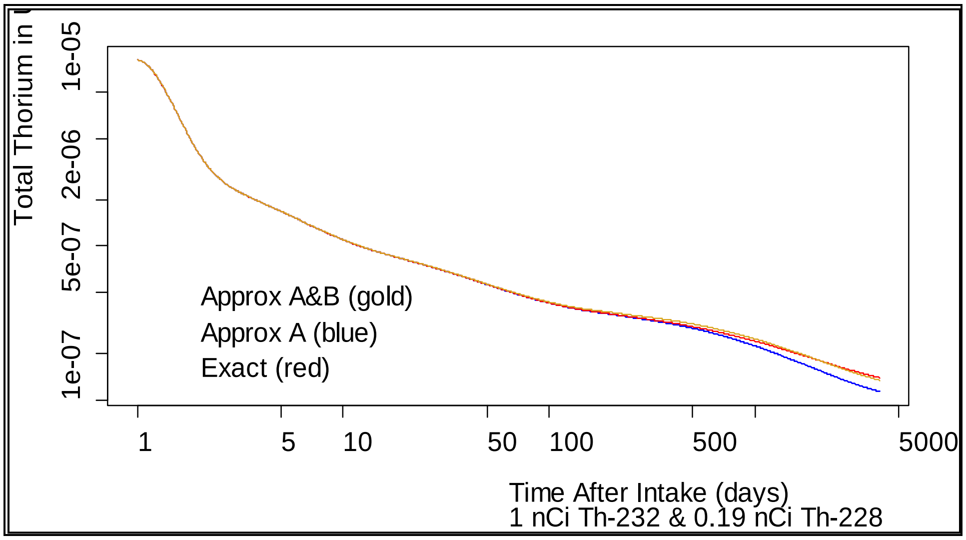

Figure 9-3. Thorium urine content after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 showing excretion with Approximation A (blue line) and with Approximations A and B (gold line).

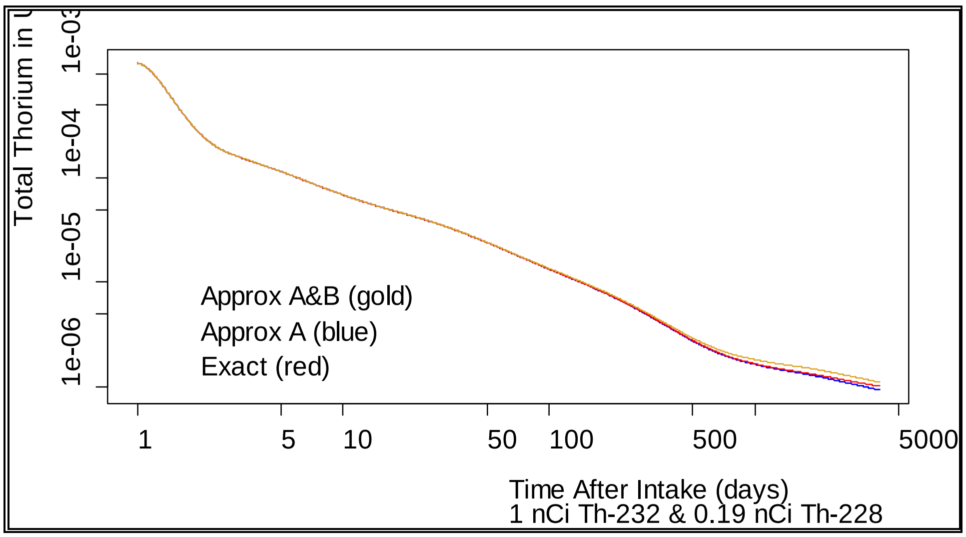

Figure 9-4. Thorium urine content after an acute inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1 showing excretion with Approximation A (blue line) and with Approximations A and B (gold line).

9.2 CHRONIC INTAKES

The plot in Figure 9-5 shows the thorium content of a 24-hour incremental urine sample as a function of time after a chronic intake of 1 nCi/d of ^{232}Th and 0.19 nCi/d of ^{228}Th (both being 5-µm AMAD Type S material). The time on the abscissa is the length of time after the start of the chronic intake that the urine sample was completed. The actual length of the chronic intake is 1 day less than the day the urine sample was completed (i.e., urine samples are not collected while the individual is being exposed).

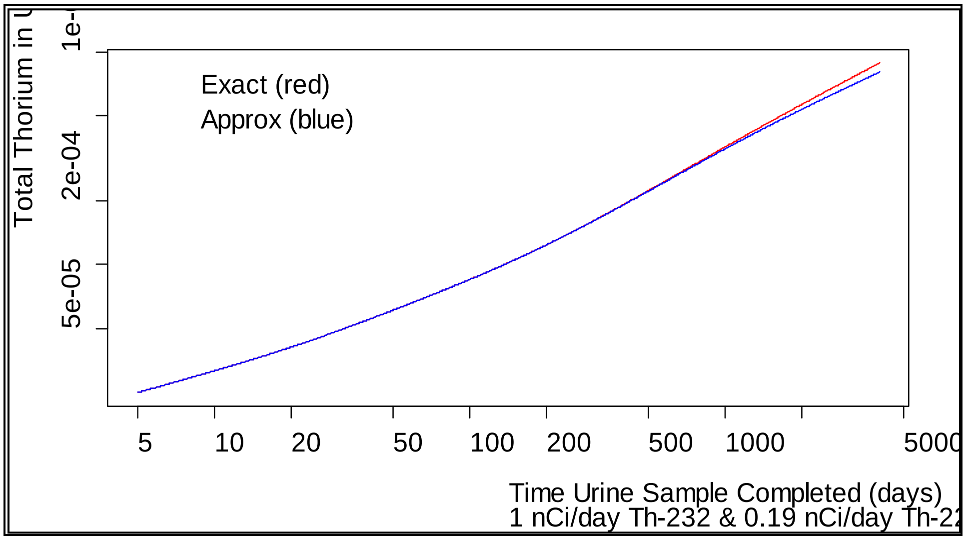

Figure 9-5. Thorium urine content after a chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

The equations for chronic intakes are essentially the same as in the case of acute intakes except that the functions have an argument for the length of the constant chronic intake period. The exact thorium content *q* of a 24-hour urine sample completed at *t* days after the start of a chronic inhalation intake over t_c days is given by:

$$q(t,t_c) = q_{\text{th232}}(t,t_c) + q_{\text{thth232}}(t,t_c) + q_{\text{th228}}(t,t_c) \qquad \{t \geq t_c + 1\} \tag{9-16}$$

Applying Approximation A gives the following:

$$q(t,t_c) = q_{\text{th232}}(t,t_c) + q_{\text{th228}}(t,t_c) \qquad \{t \geq t_c + 1\} \tag{9-17}$$

In terms of intakes and IRFs:

$$q(t,t_c) = I_{\text{th232}}\tilde{m}_{\text{th232}}(t,t_c) + I_{\text{th232}}\tilde{m}_{\text{thth232}}(t,t_c) + I_{\text{th228}}\tilde{m}_{\text{th228}}(t,t_c) \qquad \{t \geq t_c + 1\} \tag{9-18}$$

and:

$$q(t,t_c) = I_{\text{th232}}\tilde{m}_{\text{th232}}(t,t_c) + I_{\text{th228}}\tilde{m}_{\text{th228}}(t,t_c) \qquad \{t \geq t_c + 1\} \tag{9-19}$$

Example 9-3

For example, assume that 0.0015 nCi of thorium is observed in a 24-hour urine sample completed on day 366 after a 365-day chronic inhalation intake of Type S triple-separated thorium. Given a ^{228}Th:^{232}Th intake ratio of 0.19:1, the total intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{\tilde{m}_{\text{th232}}(366,365) + \tilde{m}_{\text{thth232}}(366,365) + 0.19\tilde{m}_{\text{th228}}(366,365)} \\ &= \frac{0.0015\,\text{nCi}}{4.006\text{E-}07 + 1.657\text{E-}09 + (0.19)(3.500\text{E-}07)} \\ &= 3{,}200\,\text{nCi} \end{aligned} \tag{9-20}$$

which translates into 0.19 × 3,200 nCi = 608 nCi of ^{228}Th. This can be verified as accomplished before by using the intakes to calculate the ^{228}Th content of the urine sample:

$$0.0015\,\text{nCi} = (3{,}200\,\text{nCi})(4.006\text{E-}07) + (3200\,\text{nCi})(1.657\text{E-}09) + (608\,\text{nCi})(3.500\text{E-}07) \quad (9\text{-}21)$$

The intake rates are obtained by dividing the intakes by t_c = 365 days. With the application of Approximation A the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{\tilde{m}_{\text{th232}}(366,365) + 0.19\tilde{m}_{\text{th228}}(366,365)} \\ &= \frac{0.0015\,\text{nCi}}{4.006\text{E-}07 + (0.19)(3.500\text{E-}07)} \\ &= 3{,}212\,\text{nCi} \end{aligned} \quad (9\text{-}22)$$

which translates into a 610 nCi intake of ^{228}Th.

Figures 9-6 to 9-9 show the thorium urinary excretion curves for chronic intakes of Type M and S triple-separated thorium. The 15% intake adjustment applied in the acute intake case above is adequate to make chronic intake rates that are estimated with Approximations A and B not underestimate the intake rates that would be calculated with the exact method. For example, the ^{232}Th intake that was calculated with Approximations A, B, and C is:

$$I_{\text{th232}} = \frac{0.0015\,\text{nCi}}{\tilde{m}_{\text{th232}}(365,365)} = \frac{0.0015\,\text{nCi}}{4.006\text{E-}07} = 3{,}745\,\text{nCi} \quad (9\text{-}23)$$

The ^{228}Th intake is 712 nCi.

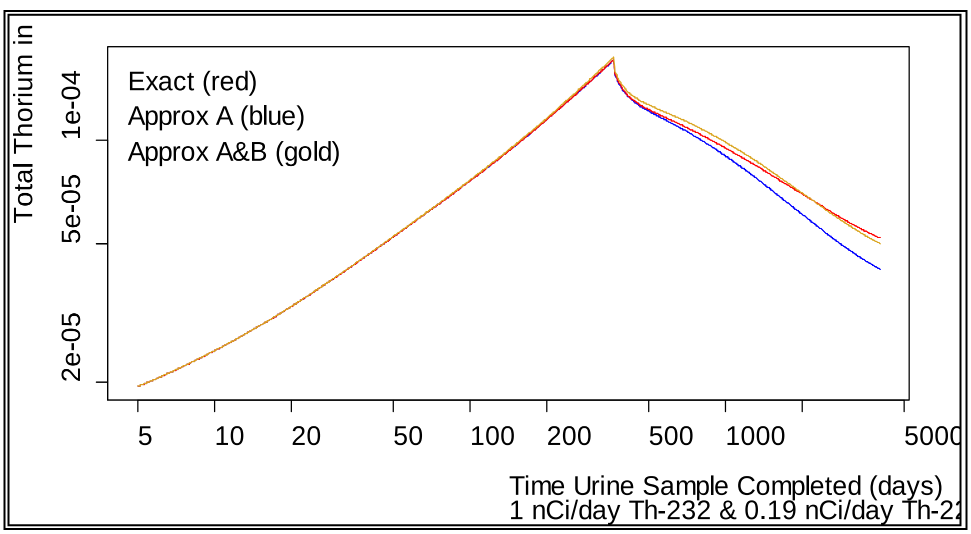

Figure 9-6. Thorium urine content after a 365-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The blue line is the excretion with Approximation A and the gold line is the excretion with Approximations A and B.

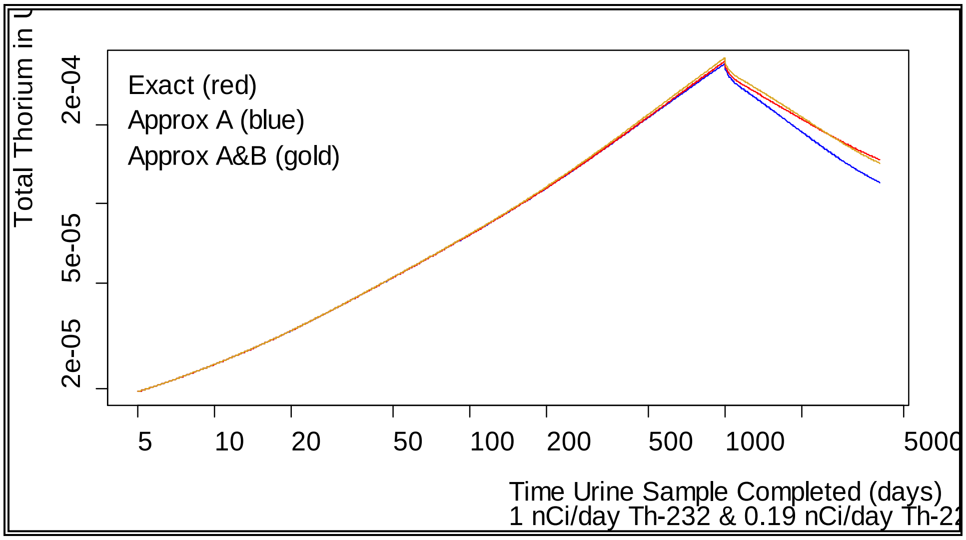

Figure 9-7. Thorium urine content after a 1,000-day chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The blue line is the excretion with Approximation A and the gold line is the excretion with Approximations A and B.

9.2.1 Guidance for Chronic Intakes

Based on the discussion above, the following guidance is offered on how to use the approximate method to evaluate thorium urine bioassay measurements after constant chronic inhalation intakes of Type M or S thorium:

Assume a single measured thorium urine bioassay result. Evaluate the result with a ^{232}Th biokinetic model in IMBA to obtain an estimate of the ^{232}Th intake rate. Multiply this estimate of the ^{232}Th intake rate by the ^{228}Th:^{232}*Th ratio of 0.19:1 to obtain the estimate of the* ^{228}Th *intake rate. These approximate intake rates will not underestimate the intake rates that would be calculated with exact methods.*

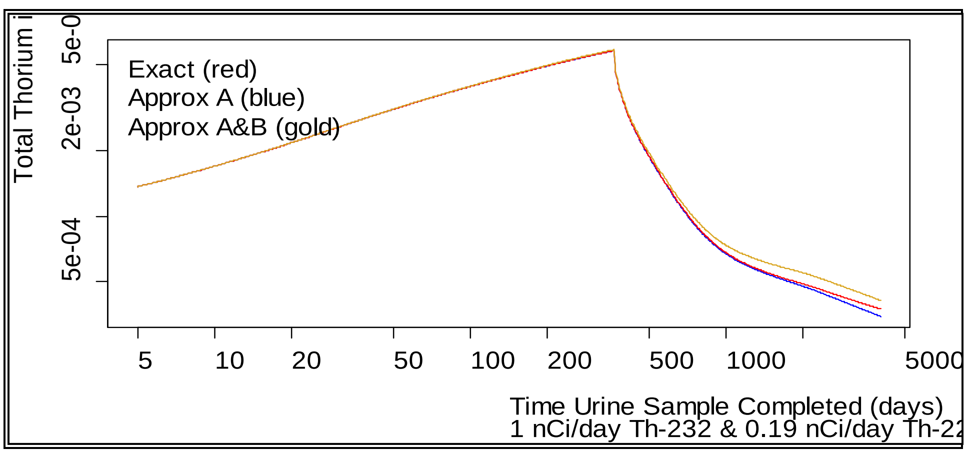

Figure 9-8. Thorium urine content after a 365-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The blue line is the excretion with Approximation A and the gold line is the excretion with Approximations A and B.

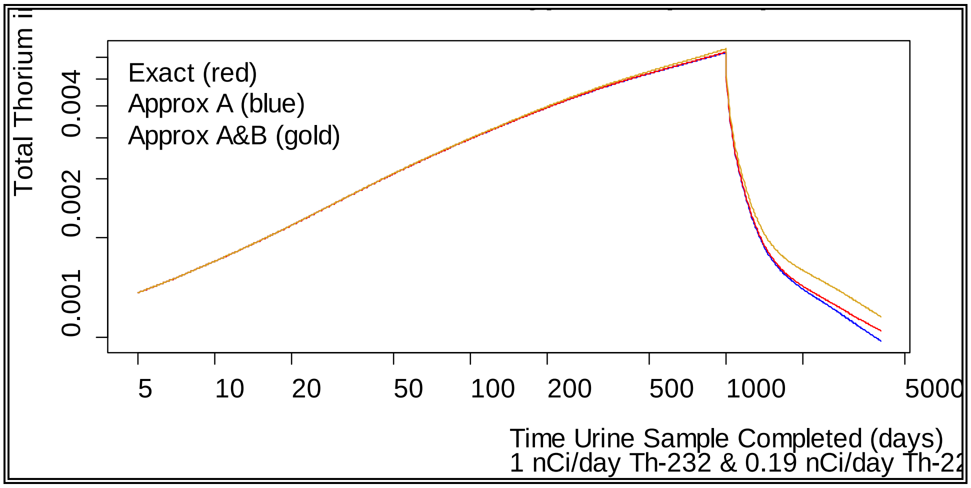

Figure 9-9. Thorium urine content after a 1,000-day chronic inhalation intake of Type M thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1. The blue line is the excretion with Approximation A and the gold line is the excretion with Approximations A and B.

10.0 USING IMBA FOR THORIUM-228 IN URINE

This section discusses adjustments to intakes and intake rates of ^{232}Th and ^{228}Th that are calculated with IMBA from ^{228}Th that is measured in urine samples so that the intakes and intake rates will not underestimate those that would be calculated with exact methods (DCAL). These adjustments may be used when an overestimate of dose is appropriate. Best estimates of dose require the use of DCAL.

10.1 ACUTE INTAKES

Assume a mixture of 1 nCi of ^{232}Th and 1 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{228}Th in 24-hour incremental urine samples as a function of time after the acute intake is shown in Figure 10-1.

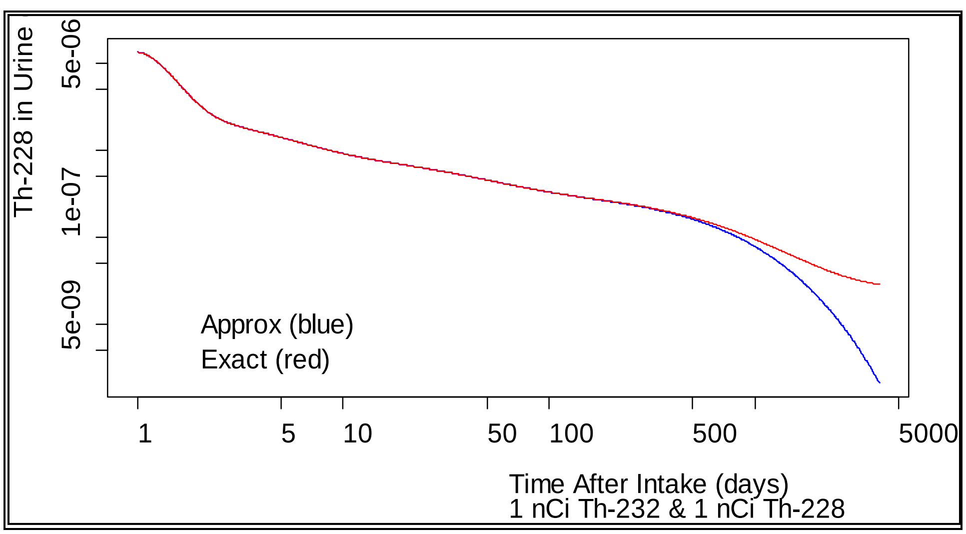

Figure 10-1. Thorium-228 in 24-hour incremental urine samples after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 1:1.

The exact content *q* of ^{228}Th in the urine at *t* days after an acute inhalation intake is given by:

$$\begin{aligned} q(t) &= q_{\text{thth232}}(t) + q_{\text{th228}}(t) \\ &= I_{\text{th232}} m_{\text{thth232}}(t) + I_{\text{th228}} m_{\text{th228}}(t) \end{aligned} \tag{10-1}$$

where q_{thth232} is the amount of ^{228}Th in the sample that grows in from the inhaled ^{232}Th and q_{th228} is the amount of ^{228}Th in the sample from the inhaled ^{228}Th. These exact contents are calculated with DCAL, which accounts for independent kinetics of the thorium decay chain and the loss of ^{220}Rn. The red excretion curve in Figure 10-1 was calculated using the exact method. An approximation that can be made here is that there is negligible ingrowth of ^{228}Th from the ^{232}Th component of the intake. That is:

$$q_{\text{thth232}}(t) = 0 \tag{10-2}$$

This gives the following approximation to *q*:

$$q'(t) = q_{\text{th228}}(t) \tag{10-3}$$

where q_{th228} is the ^{228}Th urine content at time *t* (which can be calculated with IMBA). The blue excretion curve in Figure 10-1 was calculated using the approximate method. As seen in the plot above, this approximation provides reasonably accurate estimates of the ^{228}Th urine content for a couple of years after the intake. At later times the approximate method underestimates the urinary excretion rate.

Example 10-1

For example, assume that 0.0015 nCi of ^{228}Th is observed in a 24-hour urine sample completed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 1: 1, the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{m_{\text{thth232}}(100) + m_{\text{th228}}(100)} \\ &= \frac{0.0015\,\text{nCi}}{4.64\text{E-}10 + 3.31\text{E-}07} \\ &= 4{,}525\,\text{nCi} \end{aligned} \tag{10-4}$$

which translates into 4,525 nCi of ^{228}Th. These intakes can be checked by calculating the expected ^{228}Th urine content and determining if it equals the content from which the intakes were calculated:

$$0.0015\,\text{nCi} = (4{,}525\,\text{nCi})(4.64\text{E-}10) + (4{,}525\,\text{nCi})(3.31\text{E-}07) \tag{10-5}$$

With the approximate method we have a ^{228}Th intake of:

$$I_{\text{th228}} = \frac{0.0015\,\text{nCi}}{m_{\text{th228}}(100)} = \frac{0.0015\,\text{nCi}}{3.31\text{E-}07} = 4{,}532\,\text{nCi} \tag{10-6}$$

which translates into a 4,532-nCi intake of ^{232}Th. From the equations given above it should be evident that, for a given quantity of ^{228}Th in the urine, the approximate method will always give an intake that is greater than or equal to the intake from the exact method (this is reflected in Figure 10-1). Further, this is true regardless of the ^{228}Th:^{232}Th ratio, dissolution type (M or S), or exposure pattern (acute or chronic).

10.1.1 Triple-Separated Thorium Mixture

Assume a mixture of 1 nCi of ^{232}Th and 0.19 nCi of ^{228}Th (both being 5-µm AMAD Type S material) was inhaled. The ^{228}Th urine content as a function of time after the acute intake is shown in Figure 10-2.

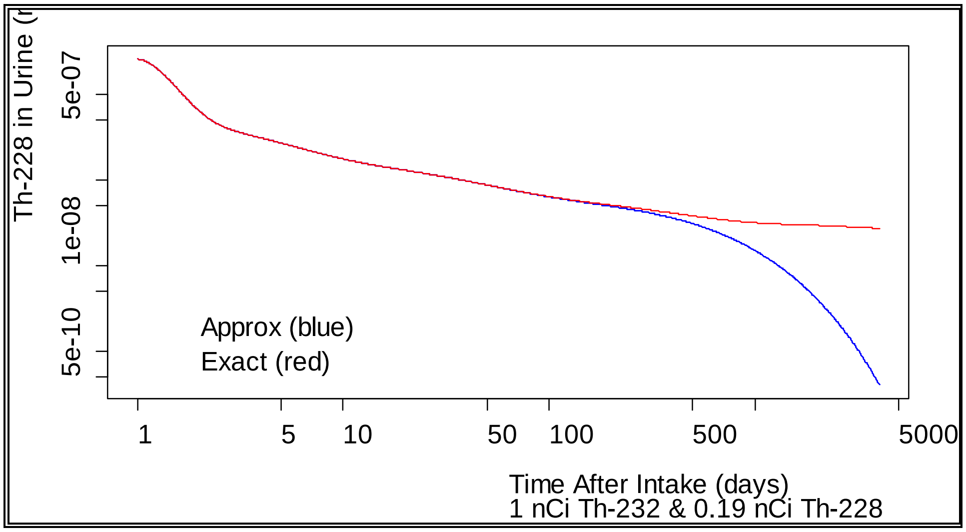

Figure 10-2. Thorium-228 urine content after an acute inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

The exact content q of ^{228}Th in the urine at t days after an acute inhalation intake is given by:

$$q(t) = q_{\text{thth232}}(t) + q_{\text{th228}}(t) \tag{10-7}$$

The approximation to q is:

$$q'(t) = q_{\text{th228}}(t) \tag{10-8}$$

In terms of intakes and IRFs:

$$q(t) = I_{\text{th232}} m_{\text{thth232}}(t) + I_{\text{th228}} m_{\text{th228}}(t) \tag{10-9}$$

$$q'(t) = I_{\text{th228}} m_{\text{th228}}(t) \tag{10-10}$$

Example 10-2

For example, assume that 0.0015 nCi of ^{228}Th is observed in a 24-hour urine sample completed at 100 days after an acute inhalation intake of this Type S thorium. Given a ^{228}Th:^{232}Th ratio of 0.19:1, the intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{m_{\text{thth232}}(100) + 0.19 m_{\text{th228}}(100)} \\ &= \frac{0.0015\,\text{nCi}}{4.64\text{E-}10 + (0.19)(3.31\text{E-}07)} \\ &= 23{,}676\,\text{nCi} \end{aligned} \tag{10-11}$$

which translates into 4,499 nCi of ^{228}Th. These intakes can be checked by calculating the expected ^{228}Th urine content and determining if it equals the content from which the intakes were calculated:

$$0.0015\,\text{nCi} = (23{,}676\,\text{nCi})(4.64\text{E-}10) + (4{,}499\,\text{nCi})(3.31\text{E-}07) \tag{10-12}$$

With the approximate method we have a ^{228}Th intake of:

$$I_{\text{th228}} = \frac{0.0015\,\text{nCi}}{m_{\text{th228}}(100)} = \frac{0.0015\,\text{nCi}}{3.31\text{E-}07} = 4{,}532\,\text{nCi} \tag{10-13}$$

which translates into 4,532 nCi ÷ 0.19 = 23,851 nCi of ^{232}Th intake.

10.1.2 Guidance for Acute Intakes

Based on discussion given above, the following guidance is offered on how to use the approximate method to evaluate ^{228}Th urine bioassay measurements after acute inhalation intakes of Type M or S thorium:

Assume a single measured ^{228}Th *urine bioassay result. Evaluate the result with a* ^{228}Th *biokinetic model in IMBA and assign it as the intake of* ^{228}Th*. Divide this estimated* ^{228}Th *intake by the* ^{228}Th:^{232}*Th ratio of 0.19:1 to obtain the* ^{232}*Th intake. These approximate intakes will not underestimate the intakes that would be calculated with exact methods.*

10.2 CHRONIC INTAKES

The plot in Figure 10-3 shows the ^{228}Th content of a 24-hour incremental urine sample as a function of time after a chronic intake of 1 nCi/d of ^{232}Th and 0.19 nCi/d of ^{228}Th (both being 5-µm AMAD Type S material). The time on the abscissa is the length of time after the start of the chronic intake that the urine sample was completed. The actual length of the chronic intake is 1 day less than the day the urine sample was completed (i.e., urine samples are not collected while the individual is being exposed).

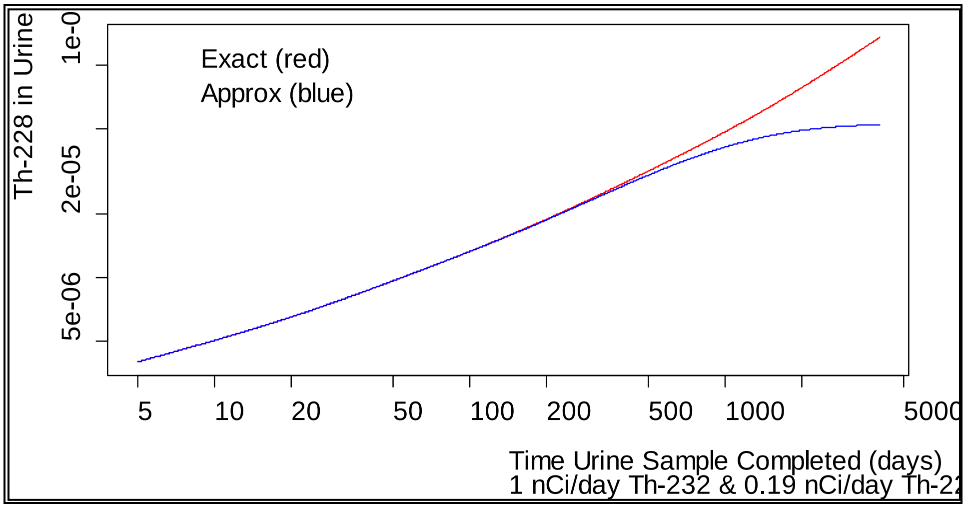

Figure 10-3. Thorium-228 urine content after a chronic inhalation intake of Type S thorium having a ^{228}Th to ^{232}Th ratio of 0.19:1.

The equations for chronic intakes are essentially the same as in the case of acute intakes except that the functions have an argument for the length of the constant chronic intake period. The exact ^{228}Th content q of a 24-hour urine sample completed at t days after the start of a chronic inhalation intake over t_c days is given by:

$$q(t,t_c) = q_{\text{thth232}}(t,t_c) + q_{\text{th228}}(t,t_c) \qquad \{t \geq t_c + 1\} \tag{10-14}$$

Applying the approximation gives the following:

$$q'(t,t_c) = q_{\text{th228}}(t,t_c) \tag{10-15}$$

In terms of intakes and IRFs:

$$q(t,t_c) = I_{\text{th232}}\tilde{m}_{\text{thth232}}(t,t_c) + I_{\text{th228}}\tilde{m}_{\text{th228}}(t,t_c) \tag{10-16}$$

$$q'(t) = I_{\text{th228}} m_{\text{th228}}(t) \tag{10-17}$$

Example 10-3

For example, assume that 0.0015 nCi of ^{228}Th is observed in a 24-hour urine sample completed on day 366 after a 365-day chronic inhalation intake of Type S triple-separated thorium. Given a ^{228}Th:^{232}Th ratio of 0.19:1, the total intake of ^{232}Th is:

$$\begin{aligned} I_{\text{th232}} &= \frac{0.0015\,\text{nCi}}{\tilde{m}_{\text{thth232}}(366,365) + 0.19\tilde{m}_{\text{th228}}(366,365)} \\ &= \frac{0.0015\,\text{nCi}}{1.657\text{E-09} + (0.19)(3.500\text{E-07})} \\ &= 22{,}007\ \text{nCi} \end{aligned} \tag{10-18}$$

which translates into 0.19 × 22,007 nCi = 4,181 nCi of ^{228}Th. This can be verified as accomplished before by using the intakes to calculate the ^{228}Th content of the urine sample:

$$0.0015\,\text{nCi} = (22{,}007\,\text{nCi})(1.657\text{E-09}) + (4{,}181\,\text{nCi})(3.500\text{E-07}) \tag{10-19}$$

The intake rates are obtained by dividing the intakes by t_c = 365 days. With the approximate method the intake of ^{228}Th is:

$$\begin{aligned} I_{\text{th228}} &= \frac{0.0015\,\text{nCi}}{\tilde{m}_{\text{th228}}(365,365)} \\ &= \frac{0.0015\,\text{nCi}}{(3.500\text{E-07})} \\ &= 4{,}286\,\text{nCi} \end{aligned} \tag{10-20}$$

which gives 4,286 nCi ÷ 0.19 = 22,556 nCi of ^{232}Th.

10.2.1 Guidance for Chronic Intakes

Based on discussion above, the following guidance is offered on how to use the approximate method to evaluate ^{228}Th urine bioassay measurements after constant chronic inhalation intakes of Type M or S thorium:

Assume a single measured ^{228}Th *urine bioassay result. Evaluate the result with a* ^{228}Th *biokinetic model in IMBA and assign it as the intake rate of* ^{228}Th. *Divide this estimated* ^{228}Th *intake rate by the* ^{228}Th:^{232}*Th ratio of 0.19:1 to obtain the* ^{232}*Th intake rate. These approximate intake rates will not underestimate the intake rates that would be calculated with exact methods.*

11.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

REFERENCES

ICRP (International Commission on Radiological Protection, 1979–1988, *Limits for Intakes of Radionuclides by Workers*, Publication 30, Parts 1–4 and Supplements, Pergamon Press, Oxford England. [SRDB Ref ID: 22733]

ICRP (International Commission on Radiological Protection, 1995, *Dose Coefficients for Intakes of Radionuclides by Workers*, Publication 68, Pergamon Press, Oxford England. [SRDB Ref ID: 22731]

ATTACHMENT A
STANDARD THORIUM MIXTURES

LIST OF TABLES

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ATTACHMENT A
STANDARD THORIUM MIXTURES (continued)

To accurately evaluate a ^{212}Pb or ^{228}Ac chest count in terms of an intake of thorium, the relative amounts of ^{232}Th, ^{228}Ra, and ^{228}Th in the inhaled material have to be known. In certain cases a mixture of radionuclides can be specified that will provide a conservative estimate of the intake. These *standard thorium mixtures* are defined in this attachment.

Assume 1 Bq of ^{232}Th in equilibrium with all of its progeny chemically stripped of everything except for the ^{232}Th and ^{228}Th. The time at which this occurs is referred to as t = 0 years. The activity of ^{228}Th that is present in the source at various times after t = 0 years is shown in Figure A-1 (the activity of ^{232}Th is constant at 1 Bq). The ^{228}Th activity hits a minimum of 0.42 Bq at 4.55 years.

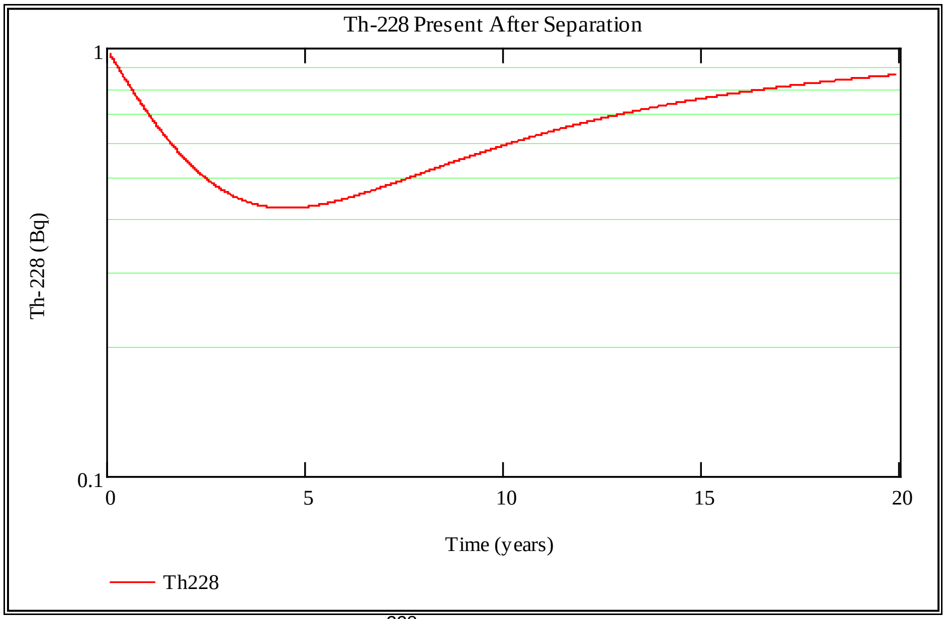

Figure A-1. Thorium-232 and ^{228}Th present as a function of time after separation of thorium from other elements in the decay chain. At the time of separation all members of the decay chain were in equilibrium with the ^{232}Th.

For all practical applications ^{224}Ra, with a half-life of 3.66 days, is always in secular equilibrium with ^{228}Th. However, ^{228}Ra, with its half-life of 5.75 years is depleted and takes years to grow back to any significant degree. These progeny are important because ^{212}Pb (which can be measured in vivo) is in secular equilibrium with the ^{224}Ra (which cannot be measured in vivo) and ^{228}Ac (which can be measured in vivo) is in secular equilibrium with the ^{228}Ra (which cannot be measured in vivo). The ingrowth curves for ^{224}Ra and ^{228}Ra are shown in Figure A-2. The minimum in the ^{224}Ra curve coincides with the minimum in the ^{228}Th curve.

If there is a second separation at 4.55 years after the first, the thorium will have the ^{228}Th ingrowth curve shown in Figure A-3, which has a minimum of 0.26 Bq at 2.54 years after the second separation (or 2.54 + 4.55 = 7.09 years after the first separation).

The corresponding ^{224}Ra and ^{228}Ra curves after the second separation are shown in Figure A-4.

If there is a third separation at 7.09 years after the first, the thorium will have the ^{228}Th ingrowth curve shown in Figure A-5, which has a minimum of 0.19 Bq at 1.75 years after the third separation (or 1.75 + 2.54 + 4.55 = 8.84 years after the first separation).

ATTACHMENT A
STANDARD THORIUM MIXTURES (continued)

The corresponding ^{224}Ra and ^{228}Ra curves after the third separation are shown in Figure A-6.

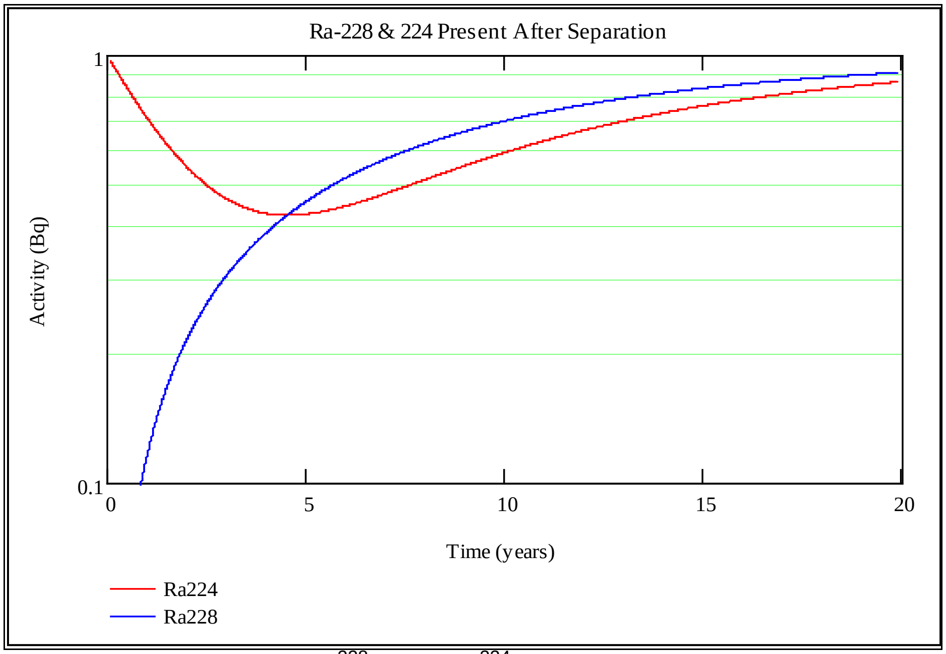

Figure A-2. Thorium-232, ^{228}Ra, and ^{224}Ra present after separation of thorium from other elements in the decay chain. At the time of separation all members of the decay chain were in equilibrium with the ^{232}Th.

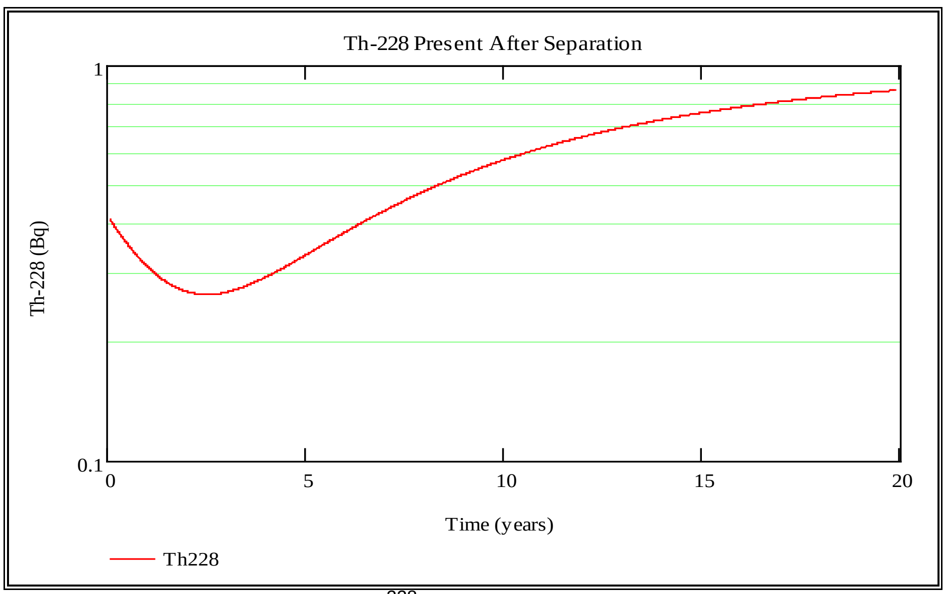

Figure A-3. Thorium-232 and ^{228}Th present as a function of time after a second separation of thorium from other elements in the decay chain. At the time of separation 4.55 years had elapsed since the first separation.

ATTACHMENT A
STANDARD THORIUM MIXTURES (continued)

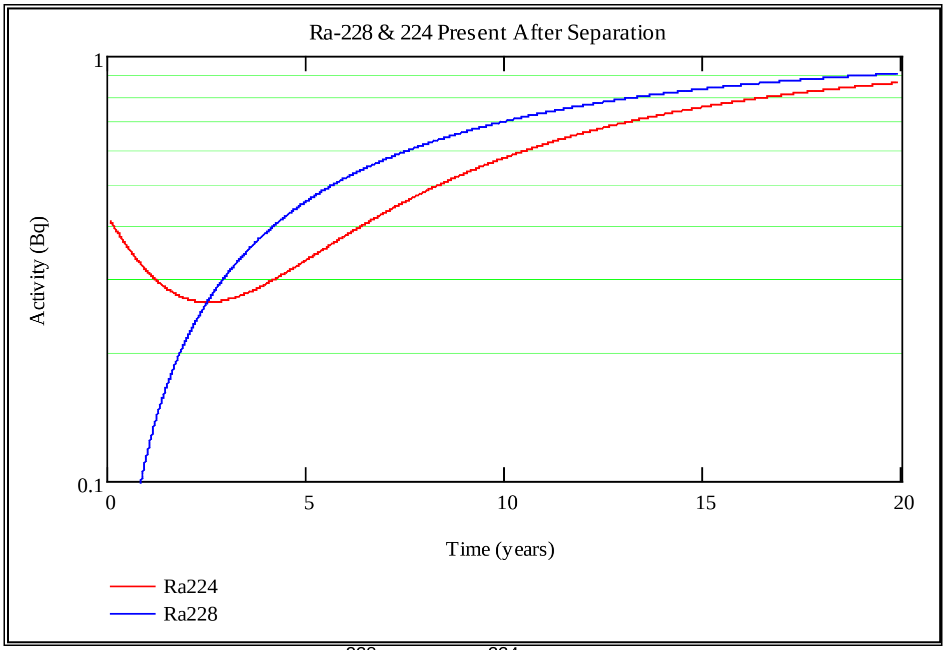

Figure A-4. Thorium-232, ^{228}Ra, and ^{224}Ra present as a function of time after a second separation of thorium from other elements in the decay chain. At the time of separation 4.55 years had elapsed since the first separation.

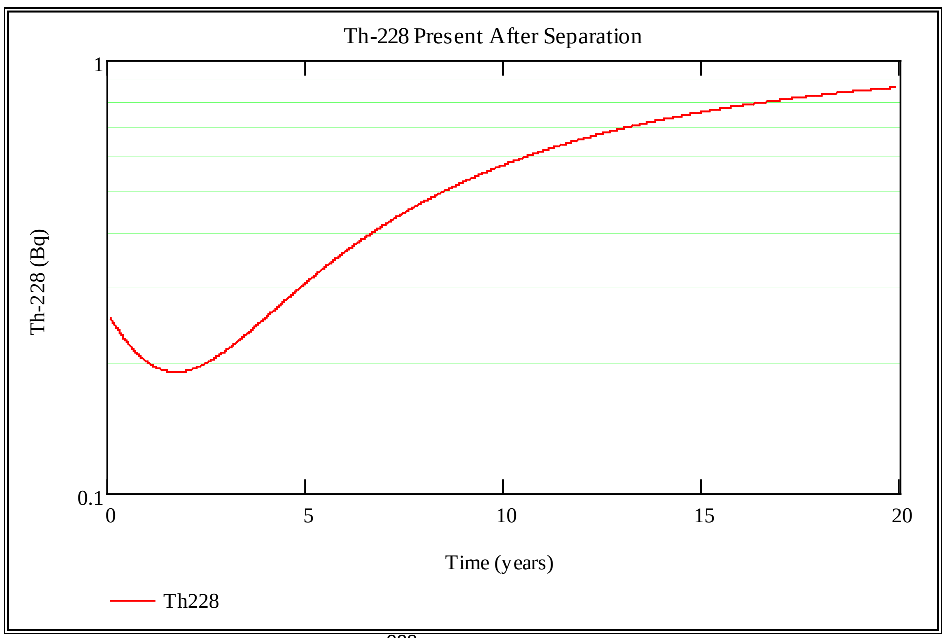

Figure A-5. Thorium-232 and ^{228}Th present as a function of time after a third separation of thorium from other elements in the decay chain. At the time of separation 7.086 years had elapsed since the first separation.

ATTACHMENT A
STANDARD THORIUM MIXTURES (continued)

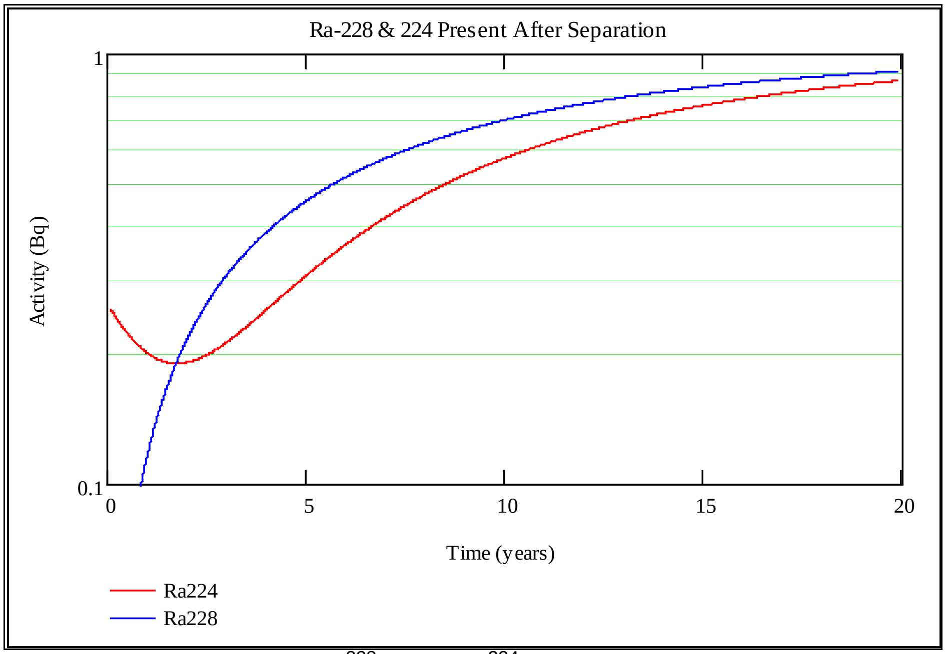

Figure A-6. Thorium-232, ^{228}Ra, and ^{224}Ra present as a function of time after a third separation of thorium from other elements in the decay chain. At the time of separation 7.086 years had elapsed since the first separation.

These data are summarized in Table A-1. The ratio of ^{228}Th activity to ^{232}Th activity is shown for the cases of secular equilibrium (no chemical separation), a single chemical separation at *t* = 0 years, a second chemical separation at *t* = 4.550 years, and a third chemical separation at *t* = 7.086 years. Note that these chemical separations are timed to produce the greatest possible reduction of the ^{228}Th/^{232}Th ratio.

Table A-1. Ratios of ^{228}Th to ^{232}Th activities for secular equilibrium and after one, two, and three chemical separations.

Time (yr)	No separations Th-228 (nCi/nCi ^{232}Th)	One separation Th-228 (nCi/nCi ^{232}Th)	Two separations Th-228 (nCi/nCi ^{232}Th)	Three separations Th-228 (nCi/nCi ^{232}Th)
0.000	**1.000**	1.0000	1.0000	1.0000
4.550	1.000	**0.4221**	0.4221	0.4221
7.086	1.000	0.4771	**0.2633**	0.2633
8.840	1.000	0.5446	0.3010	**0.1905**

Therefore, the standard thorium mixtures are:

- Unseparated (equilibrium) thorium, which has a 1:1 ^{228}Th to ^{232}Th ratio;
- Single-separated thorium, which has a 0.42:1 ^{228}Th to ^{232}Th ratio;
- Double-separated thorium, which has a 0.26:1 ^{228}Th to ^{232}Th ratio; and
- Triple-separated thorium, which has a 0.19:1 ^{228}Th to ^{232}Th ratio.

ATTACHMENT A
STANDARD THORIUM MIXTURES (continued)

Note that there is no ^{228}Ra in these standard mixtures and that once a mixture is selected for a particular application it is assumed to be a constant and does not change as a function of time. For example, if triple-separated thorium is chosen for a facility during 1980 then the same mixture applies in 1995; that is, there is no ingrowth of ^{228}Th during the 15 years.

The standard thorium mixtures give conservative ^{228}Th to ^{232}Th ratios that are independent of the age of the thorium. This means that to evaluate a ^{212}Pb chest count we have to specify the number of separations the material has gone through but not the time since separation (i.e., the age of the thorium). To evaluate an ^{228}Ac chest count the age of the standard thorium mixture has to be specified because the quantity of parent ^{228}Ra present is a strong function of the age of the thorium and an age that results in useful, conservative intake estimates cannot be specified. Relative quantities of ^{232}Th, ^{228}Ra, and ^{228}Th present in single separated thorium (which is the most conservative mixture for evaluating ^{228}Ac chest counts) as a function of time since separation are presented in Table A-2. In practice, one would specify the date that thorium separation activities ended at a given site and the minimum elapsed time between this date and the dates of the chest counts. The activity ratios for that elapsed time would be used to evaluate all ^{228}Ac chest counts.

Table A-2. Relative amounts of ^{232}Th, ^{228}Ra, and ^{228}Th in single separated thorium as a function of time since separation.

Years	Th-232	Ra228	Th228
0.5	1.000	0.058	0.839
1.0	1.000	0.114	0.715
2.0	1.000	0.214	0.548
3.0	1.000	0.303	0.461
4.0	1.000	0.383	0.426
5.0	1.000	0.453	0.425
6.0	1.000	0.515	0.443
7.0	1.000	0.570	0.474
8.0	1.000	0.619	0.511
9.0	1.000	0.662	0.551
10.0	1.000	0.700	0.591
11.0	1.000	0.734	0.630
12.0	1.000	0.765	0.667
13.0	1.000	0.791	0.701
14.0	1.000	0.815	0.732
15.0	1.000	0.836	0.761
16.0	1.000	0.855	0.787
17.0	1.000	0.871	0.810
18.0	1.000	0.886	0.831
19.0	1.000	0.899	0.850
20.0	1.000	0.910	0.867

ATTACHMENT B
OBTAINING CHRONIC INTAKE IRFs FROM ACUTE INTAKE IRFs

LIST OF FIGURES

ATTACHMENT B
OBTAINING CHRONIC INTAKE IRFs FROM ACUTE INTAKE IRFs (continued)

DCAL can provide acute intake IRFs but not chronic intake IRFs. However, this is not a major problem because a convolution integral can be used to calculate chronic intake IRFs from values of the acute intake IRFs.

To illustrate the technique, assume that the fractional retention of the hypothetical radioactive material[6] in the whole body (the intake retention function or IRF) after an acute instantaneous uptake to the bloodstream is described by the following equation:

$$m(t) = \exp\left(-\frac{\ln(2)}{10\,\mathrm{d}}t\right) \tag{B-1}$$

A plot of the whole-body retention after a unit uptake is shown in Figure B-1, where $q(t)$ is the content of the whole body at t days after the uptake.

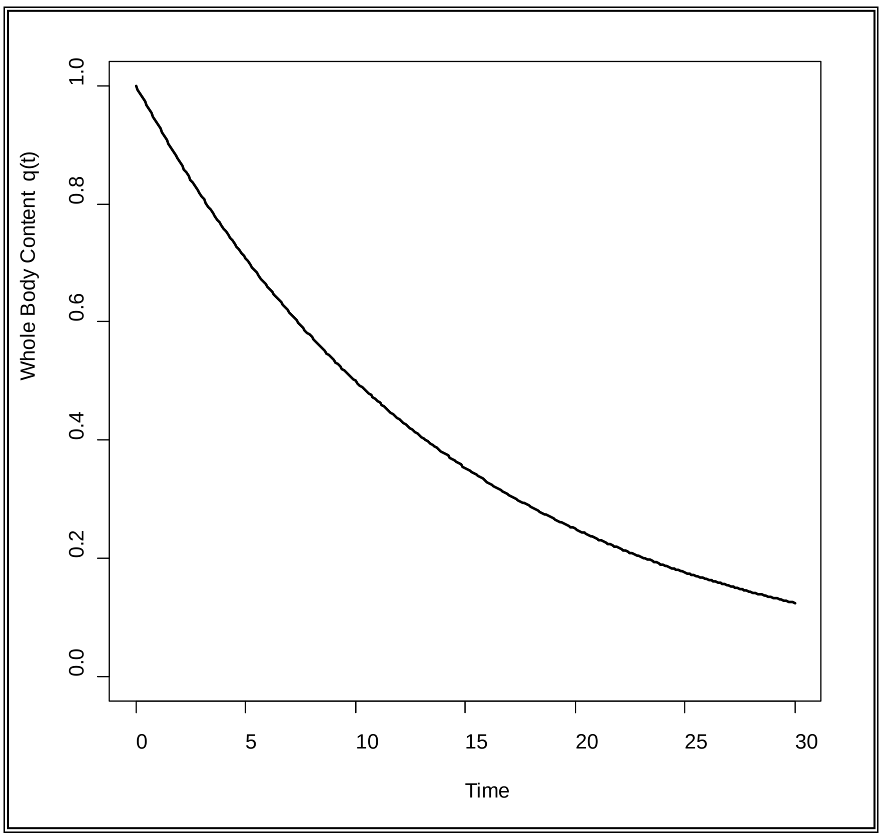

Figure B-1. Plot of whole-body retention versus time after an acute uptake of the hypothetical radioactive material.

[6] A biological half-life of 11.25 days is combined with a radiological half-life of 90 days to produce the effective half-life of 10 days used here.

ATTACHMENT B
OBTAINING CHRONIC INTAKE IRFs FROM ACUTE INTAKE IRFs (continued)

The IRF is typically used to calculate an acute intake I from the measured whole-body content (i.e., the bioassay result). For example, if the whole-body content is measured to be 100 Bq at 25 days after the acute intake, the intake is estimated to be:

$$I = \frac{q(25\,\mathrm{d})}{m(25\,\mathrm{d})} = \frac{100\,\mathrm{Bq}}{\exp\left(-\frac{\ln(2)}{10\,\mathrm{d}}25\,\mathrm{d}\right)} = 566\,\mathrm{Bq} \tag{B-2}$$

To do the same sort of calculation for a constant chronic intake, given only the acute intake IRFs and the measured whole-body content, assume the following variables and constants, which are used to construct the plot of the predicted whole-body retention versus time:

- T = length of chronic intake period = 15 days
- t = time that $q(t)$ is measured relative to start of chronic intake = 25 days
- τ = variable time in days
- d_τ = infinitesimally short time increment in days
- $\dot{I}$ = the unit intake rate = 1 Bq/d
- I = $\dot{I}T$ = the total intake = 15 Bq

The convolution integral[7] for the curve in Figure B-2 is:

$$q(t) = \int_{\tau=0}^{\tau=T} \left[\dot{I}d_\tau\right]\left[m(t-\tau)\right] \tag{B-3}$$

Note that $\dot{I}d_\tau$ is an infinitesimally small intake at time τ and that $m(t-\tau)$ is the acute retention function for that intake. Summing up all the infinitesimally small intakes from time 0 days to time T days gives the content of the whole body at t days resulting from the chronic intake.

To solve the integral, first change variables:

$$\begin{aligned} x &= t-\tau \\ t &= x+\tau \\ dx &= -d_\tau \end{aligned} \tag{B-4}$$

Then express the lower and upper limits in terms of the new variables:

$$\begin{aligned} \tau &= 0 = t-x \\ x &= t \end{aligned} \quad \text{lower limit} \tag{B-5}$$

$$\begin{aligned} \tau &= T = t-x \\ x &= t-T \end{aligned} \quad \text{upper limit} \tag{B-6}$$

---

[7] Note that the IRF must include radiological removal (i.e., the stable element IRF cannot be used here).

ATTACHMENT B
OBTAINING CHRONIC INTAKE IRFs FROM ACUTE INTAKE IRFs (continued)

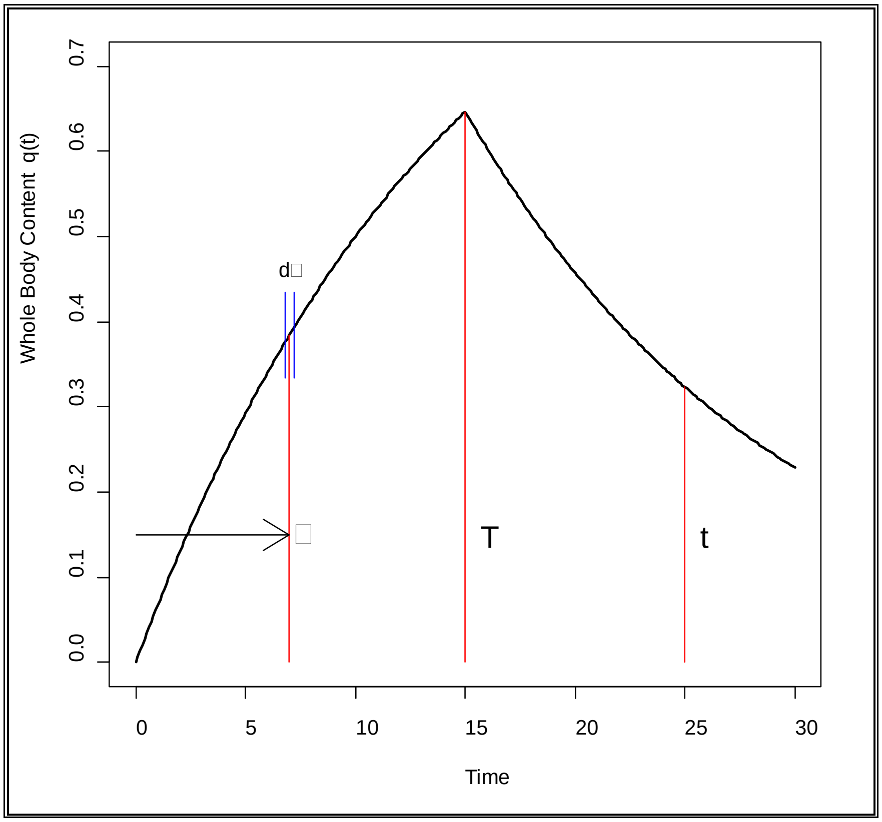

Figure B-2. Plot of whole-body retention versus time for a constant chronic uptake.

This gives the following integral:

$$q(t) = \int_{x=t}^{x=t-T} \left[-\dot{I}dx\right]\left[m(x)\right] \tag{B-7}$$

Pulling the constant intake rate outside of the integral and reversing the limits puts the integral in a form more suitable for solving:

$$q(t) = \dot{I} \int_{x=t-T}^{x=t} m(x)dx \tag{B-8}$$

This can in turn be rearranged to give:

$$I = \frac{q(t)}{\frac{1}{T}\int_{x=t-T}^{x=t} m(x)dx} \tag{B-9}$$

ATTACHMENT B
OBTAINING CHRONIC INTAKE IRFs FROM ACUTE INTAKE IRFs (continued)

or:

$$I = \frac{q(t)}{\tilde{m}(t,T)} \qquad \text{(B-10)}$$

where:

$$\tilde{m}(t,T) = \frac{1}{T}\int_{x=t-T}^{x=t} m(x)\,dx \qquad \text{(B-11)}$$

is the chronic intake retention function. For the simple example given here the integral can be solved analytically:

$$\tilde{m}(10\,\mathrm{d}, 25\,\mathrm{d}) = \left(\frac{1}{15\,\mathrm{d}}\right)\int_{10\,\mathrm{d}}^{25\,\mathrm{d}} \exp\left(-\frac{\ln(2)}{10\,\mathrm{d}}x\right)dx = 0.3108667 \qquad \text{(B-12)}$$

Once again assuming $q(25\text{ d}) = 100$ Bq:

$$I = \frac{q(t)}{\tilde{m}(t,T)} = \frac{100\,\mathrm{Bq}}{0.3108667} = 322\,\mathrm{Bq} \qquad \text{(B-13)}$$

DCAL generates tables of acute IRFs for a range of times. These tabulated values are used to create an interpolation function that gives the value of the IRF for any given time. The interpolation function is then numerically integrated to yield a chronic intake IRF as described above. These calculations were performed with a script written in the R programming language.

ATTACHMENT C
SUMMARY OF GUIDANCE FOR ASSESSING THORIUM INTAKES FROM BIOASSAY

Triple-separated thorium is assumed in the guidance given below. This is applied as a favorable to claimant assumption in the absence of more specific information. If the details of processing are known at a site, these should be used. These methods are approximations and result in intakes that will not underestimate the intakes that would be calculated with exact methods. Approximate methods are not available for ^{228}Ac chest counts, so such cases must be evaluated with exact methods. Contact the Principal Internal Dosimetrist when a best estimate or evaluation of an ^{228}Ac chest count is needed.

Chronic Intakes

Given a single ^{212}Pb chest count result for a chronic intake longer than 1 year:

1. Evaluate the chest burden using the ^{228}Th biokinetic model in IMBA.
2. Multiply the intake rate obtained in step 1 by a factor of 1.1 and assign it as the intake rate of ^{228}Th.
3. Divide the ^{228}Th intake rate by 0.19 to obtain the ^{232}Th intake rate.

Given a single ^{212}Pb whole body count result for a chronic intake longer than 1 year:

1. Evaluate the whole-body burden using the ^{228}Th biokinetic model in IMBA.
2. Multiply the intake rate obtained in step 1 by a factor of
   a. 1.5 for an intake of Type M material
   b. 1.2 for an intake of Type S material
3. Assign the result from step 2 as the intake rate of ^{228}Th.
4. Divide the ^{228}Th intake rate by 0.19 to obtain the ^{232}Th intake rate.

Given a single total thorium urine bioassay result:

1. Evaluate the urine result using the ^{232}Th biokinetic model in IMBA to obtain the ^{232}Th intake rate.
2. Multiply the ^{232}Th intake rate by 0.19 to obtain the ^{228}Th intake rate.

Given a single ^{228}Th urine bioassay result:

1. Evaluate the urine result using the ^{228}Th biokinetic model in IMBA to obtain the ^{228}Th intake rate.
2. Divide the ^{228}Th intake rate by 0.19 to obtain the ^{232}Th intake rate.

Acute Intakes

Given a single ^{212}Pb chest count result more than 30 days after an acute intake:

1. Evaluate the chest count using the ^{228}Th biokinetic model in IMBA.
2. Multiply the intake obtained in step 1 by a factor of 1.1 and assign it as the intake of ^{228}Th.
3. Divide the ^{228}Th intake by 0.19 to obtain the ^{232}Th intake.

ATTACHMENT C
SUMMARY OF GUIDANCE FOR ASSESSING THORIUM INTAKES FROM BIOASSAY (continued)

Given a single ^{212}Pb whole body count result more than 30 days after an acute intake:

1. Evaluate the whole-body burden using the ^{228}Th biokinetic model in IMBA.
2. Multiply the intake in step 1 by a factor of
    a. 1.5 for an intake of Type M material
    b. 1.2 for an intake of Type S material
3. Assign the result from step 2 as the intake of ^{228}Th.
4. Divide the ^{228}Th intake by 0.19 to obtain the ^{232}Th intake rate.

Given a single total thorium urine bioassay result:

1. Evaluate the urine result using the ^{232}Th biokinetic model in IMBA to obtain the ^{232}Th intake.
2. Multiply the ^{232}Th intake by 0.19 to obtain the ^{228}Th intake.

Given a single ^{228}Th urine bioassay result:

1. Evaluate the urine result using the ^{228}Th biokinetic model in IMBA to obtain the ^{228}Th intake.
2. Divide the ^{228}Th intake by 0.19 to obtain the ^{232}Th intake.