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A Review of ORAUT-OTIB-0076 on Guiding Reconstruction of Intakes of Thorium Resulting from Nuclear Weapons Programs

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Abbreviations and Acronyms

ABRWH, Board	Advisory Board on Radiation and Worker Health
Ac	actinium
Bq	becquerel
Bq/d	becquerel per day
CDC	Centers for Disease Control and Prevention
DCAL	Dose and Risk Calculation software
DOE	U.S. Department of Energy
DR	dose reconstruction
EPA	U.S. Environmental Protection Agency
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IRF	intake retention fraction
NIOSH	National Institute for Occupational Safety and Health
ORAUT	Oak Ridge Associated Universities Team
ORNL	Oak Ridge National Laboratory
Pb	lead
pCi	picocurie
Po	polonium
Ra	radium
Rn	radon
Th	thorium
WBC	whole-body count

1 Introduction

To support dose reconstruction (DR), the National Institute for Occupational Safety and Health (NIOSH) and the Oak Ridge Associated Universities Team (ORAUT) assembled a large body of guidance documents, workbooks, computer codes, and tools. One of those documents is ORAUT-OTIB-0076, revision 00, "Guiding Reconstruction of Intakes of Thorium Resulting from Nuclear Weapons Programs" (ORAUT, 2014; "OTIB-0076"), which provides information to allow ORAUT dose reconstructors to assign thorium intakes for overestimating dose in DR cases.

On November 8, 2024, SC&A was tasked by the Subcommittee for Procedure Reviews to review OTIB-0076. This report summarizes SC&A's review.

2 Background

OTIB-0076, page 8, summarizes the issues associated with the thorium decay chain in determining thorium intakes:

> Thorium [Th]-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.

Figure 1 shows SC&A's summary of the thorium decay chain.

Figure 1. Summary of thorium decay chain

Th-232 → Ra-228 → Ac-228 → Th-228 → Ra-224 → Rn-220 → Po-216 → Pb-212

The derivation of a thorium intake involves the consideration of many variables. Some of the major variables addressed in OTIB-0076 are summarized as follows:

- **Chemical separation:** Chemical processing of thorium disrupts equilibrium by separating the members of the decay chain based on what element they are and causes the progeny to be present in varying amounts that change over time. This disequilibrium complicates evaluating bioassay data because dose reconstructors need to specify the nature of the disequilibrium to evaluate bioassay data. Therefore, the number of times thorium has been chemically separated from its decay products and time of intake since the last separation are important. In OTIB-0076, single, double, and triple separations are considered. If unknown, use of triple separation is most claimant favorable. Chemical separation of thorium is discussed in detail in attachment A of OTIB-0076.

- **Chronic or acute intake:** OTIB-0076 addressed both chronic (over an extended period) and acute (short period) intakes of thorium for each of the most common bioassay methods.

- **Shared versus independent biological kinetics:** Shared kinetics assumes that all members of the decay chain have the same biokinetics as Th-232 (i.e., all progenies are transported, deposited, and retained in the body like the parent). The Integrated Modules for Bioassay Analysis (IMBA) program applies the same biological kinetics (referred to as "biokinetics" or "kinetics" in OTIB-0076) to all the thorium decay products as are used for thorium. Independent kinetics assumes that all members of the decay chain have biokinetics based on the element, which can be very different than the biokinetics of thorium. The Dose and Risk Calculation software (DCAL) uses independent kinetics for each individual radioisotope in the thorium decay chain.

- **Bioassay method:** OTIB-0076 develops method for estimating thorium intakes from four common bioassay methods:
    - chest counts
    - whole-body counts (WBCs)
    - total thorium in urine
    - Th-228 in urine

Fecal monitoring can also be used to bound thorium intake (NIOSH, 2018); however, OTIB-0076 does not address that method. OTIB-0076 does develop methods to estimate thorium intakes to encompass these variables and the four above listed bioassay methods using DCAL and IMBA modeling. DCAL was developed by the U.S. Environmental Protection Agency (EPA, 2006) to model radionuclide intakes using independent kinetics. Independent kinetics are also used in International Commission on Radiological Protection (ICRP) Publication 68 (ICRP, 1994); whereas ICRP Publication 30 used shared kinetics (ICRP, 1979, 1980, 1981, 1988). Refer to appendix A of this report for a summary of DCAL.

3 ORAUT-OTIB-0076 Purpose

The purpose of OTIB-0076 (ORAUT, 2014) is to provide information to dose reconstructors on how to (1) evaluate chest counts, WBCs, and various types of urine samples for an energy employee that has had an uptake of Th-232 and (2) calculate a conservative intake using IMBA. To account for disequilibrium and independent kinetics, NIOSH initially used DCAL in their computational methods. However, according to section 6.0 of OTIB-0076 (p. 25):

> 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.

OTIB-0076 uses efficiency calculations when an overestimate of dose is appropriate and a single measurement is being evaluated. OTIB-0076 cannot be used to perform best estimate or underestimating DRs of thorium intakes based on bioassay data because it uses adjustment

factors that overestimate thorium intake compared to those derived using DCAL computations. Also, IMBA cannot be used to estimate thorium intake based on actinium (Ac)-228 WBC, or directly from lead (Pb)-212 chest counts (Ac-228 and Pb-212 are not selectable in IMBA's radioisotope selection panel). DCAL must be used to analyze Ac-228 WBC data. However, IMBA can be used to analyze Pb-212 chest count data assuming a Th-228 biokinetic model in conjunction with adjustment factors that are detailed in sections 7.0 and 8.0 of OTIB-0076.

It should be noted that OTIB-0076 uses the term "approximate" method or results when IMBA is used and "exact" method or results when DCAL is used. Additionally, the term "approximation" is used when a simplifying assumption is made (e.g., for two approximations concerning Pb-212 as in equations 7-3 and 7-4 on page 26 and for Approximations A, B, and C in equations 9-2, 9-11, and 9-15, respectively (pp. 46, 48–49)).

4 ORAUT-OTIB-0076 Methodology

OTIB-0076 develops methods to estimate thorium intakes using bioassay data by the use of intake retention fractions (IRFs). IRFs are dependent on the biological processing of the radionuclide (the chemical element), the half-life of the radioisotope, and the bioassay method.

In the equations in OTIB-0076, the symbol "m_{xxxxx}", where $xxxxx$ is the radioisotope (e.g., $Th232$), is used for the IRF. The symbol "m_{xxxxx}" has a tilde over the m ($\widetilde{m}$) when the IRF is derived for a chronic intake from a series of acute intakes, as indicated at the start of section 5.0 on page 22 of OTIB-0076. The IRF is essentially the fraction of the initial intake that will be present in the body or detected in a urine bioassay sample as a function of time (see observation 1 for details). For example, if 2.74E7 picocurie (pCi) of Th-232 is inhaled on day one (acute intake), and 100 days later a Th-232 urinalysis shows 10 pCi of Th-228, then the IRF would be 10 pCi divided by 2.74E7 pCi, which equals 3.65E-7 (example 3-3, page 14, of OTIB-0076). For a chronic intake, the intake rate is derived by dividing the total intake by the number of days of the intake, e.g., 2.74E7 pCi divided by 100 days equals 2.74E5 pCi/day. Dose reconstructors generally apply an already derived IRF (using DCAL or IMBA) to determine the potential thorium intake from a bioassay result.

Observation 1: Multiple definitions of intake retention fraction

SC&A noted that OTIB-0076, page 7, defines IRF as "intake retention factor"; however, in example 2-1, page 9, it is defined as "intake retention fraction," and on page 68 it is defined as "intake retention function." SC&A finds that the term "intake retention fraction" is more appropriate for use for DR purposes.

OTIB-0076 uses the following symbols:

- l to denote the intake of a radioisotope (e.g., an intake of 10 pCi of Th-232)
- q to denote both the whole-body content of a radioisotope and also a 24-hour urine content (e.g., 1.5 pCi of Th-228)
- q' to denote approximated whole-body content derived using Pb-212 approximation methods and also a 24-hour urine content using Approximation A

- q'' to denote a 24-hour urine content using Approximation B

In general, OTIB-0076 recommends using a third chemical separation ratio for Th-228:Th-232 of 0.19 if the chemical separation is unknown, as this is claimant favorable. This is consistent with the use of triple separation of thorium as being claimant favorable for Fernald (SC&A, 2014) and Y-12 (SC&A, 2020).

Observation 2: Multiple meanings of units

SC&A found that the symbol "*q(t)*" is used in the equations in OTIB-0076 to mean the chest or whole-body burden (i.e., the quantity of a radioisotope contained in the body, which would be the intake multiplied by the IRF) at a given time; see equation (2-1) on page 9. However, the symbol *q* also appears to have been used to mean the radioisotope content of a 24-hour urine sample (i.e., the intake multiplied by the IRF multiplied by the 24-hour urine extraction fraction), e.g., equation (2-5) on page 10. The same issue applies to the use of the symbol "*m*" in the equations. For chest or whole-body burden, "*m(t)*" is used correctly as the IRF (i.e., the fraction of a radioisotope retained in the body at a given time), e.g., equation (2-2) on page 9. However, for a 24-hour urine sample, it is used to mean the IRF multiplied by the 24-hour urine excretion fraction, e.g., equation (2-6) on page 10. This issue can be confirmed by comparing the value of $m_{th232}(100)$ equals 3.67E-2 in equation (2-4) for a chest burden with the $m_{th232}(100)$ equals 3.65E-07 in equation (2-6) for a 24-hour urine sample. The later value is smaller by a factor of five orders of magnitude, which indicates that the urine excretion fraction is included. The same issue applies to the symbol " $\widetilde{m}$," the approximated chronic IRF, used for chest or whole-body burden (equation (5-1) on page 23 compared to equation (5-10) on page 24). This did not impact the DR recommendations in attachment C of OTIB-0076 but does cause confusion when reading and understanding the contents of the document.

SC&A evaluated the methodology, equations, IMBA runs, recommendations, and documentation NIOSH used in OTIB-0076. SC&A summarizes its evaluation in the following sections.

4.1 SC&A's evaluation of equilibrium and shared kinetics

Section 2.0 of OTIB-0076 provides methods of estimating thorium intakes when thorium and its decay products are in equilibrium and all the radionuclides follow the same kinetics (i.e., the biological distribution and elimination is the same for thorium and all its decay products). This section offers methods to derive thorium intakes from chest counts, WBCs, and thorium urinalysis.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs to verify the recommendations in section 2.0 of OTIB-0076. SC&A concurs with the recommendations and had no findings in this section but did have one observation.

Observation 3: Suggested rewording in section 2.1

The first sentence in section 2.1, page 9, states, "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)." SC&A finds this sentence would better convey its meaning if it stated "when using in vivo bioassay" instead of "with in vivo bioassay."

4.2 SC&A's evaluation of disequilibrium and shared kinetics

Section 3.0 of OTIB-0076 provides methods of estimating thorium intakes when thorium and its decay products are not in equilibrium (i.e., disequilibrium) and all the radionuclides do not follow the same kinetics. This section offers methods to estimate thorium intakes from chest counts, WBCs, and urine bioassays.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs to verify the recommendations in section 3.0 of OTIB-0076. SC&A concurs with the recommendations and had no findings in this section but did have one observation.

Observation 4: Suggested clarification in section 3.1

SC&A found that the last sentence of the first paragraph on page 13 would be more technically correct if it stated: "More specifically, these thorium mixtures do not contain any ^{228}Ra at the end of separation." This modified statement, which adds "at the end of separation," is in agreement with the plot of the radium (Ra)-228 activity in figure 3-2 of OTIB-0076 that shows the ingrowth of Ra-228 as a function of time after separation.

4.3 SC&A's evaluation of exact calculations assuming independent kinetics

Section 4.0 of OTIB-0076 provides methods of estimating thorium intakes when the radionuclides follow their own independent kinetics. Independent kinetics significantly complicate the calculation of IRFs and the evaluation of bioassay data because IMBA employs shared kinetics rather than independent kinetics and cannot be used in some situations. DCAL must be used to derive thorium intakes in those situations (e.g., when using chest count or WBC bioassay data) unless the IMBA results are modified as developed in OTIB-0076 and summarized in attachment C of OTIB-0076. However, as discussed in section 4.1 of OTIB-0076, the IMBA program can be used to derive Th-228 and/or Th-232 intakes from thorium urine bioassay data because this derivation only involves thorium kinetics and does not depend on the detection of any of the decay products (such as Ac-228 or Pb-212), which would have their own independent kinetics.

SC&A evaluated the methodology and examples and ran the IMBA programs, when appropriate, to verify the recommendations in sections 4.0 and 4.1 of OTIB-0076. SC&A concurs with the recommendations and had no findings in this section but did have one observation.

Observation 5: Figure 4-3 missing

SC&A found that the bottom of page 16 of OTIB-0076 gives a caption for figure 4-3, which should show chest burdens of Th-228 and Pb-212 after a unit acute inhalation intake of pure Type S Th-228, but there is no figure provided.

4.3.1 SC&A's evaluation of chronic intakes

DCAL only provides analysis of acute intakes, not chronic. Attachment B of OTIB-0076 provides a detailed development of approximated chronic IRFs ($\widetilde{m}$) from acute IRFs (m). Section 5.0 of OTIB-0076 utilizes the information developed in attachment B to present examples of using approximated IRFs to estimate chronic intakes of thorium using bioassay data.

SC&A evaluated the methodology and examples to verify the recommendations in sections 5.0 and 5.1 of OTIB-0076. SC&A concurs with the recommendations and had no findings or observations in this section.

4.4 SC&A's evaluation of using IMBA for chest counts

Section 7.0 of OTIB-0076 provides methods and adjustment factors for estimating thorium acute intakes (section 7.1) and chronic intakes (section 7.2) from Pb-212 chest counts using the IMBA program.

4.4.1 Acute intakes

Section 7.1 of OTIB-0076 provides examples, using chest count data, of estimating thorium intakes for acute exposures using the IMBA program to derive IRFs and then compares them to the IRFs derived by using DCAL for absorption type M and S thorium. From this comparison, NIOSH develops an adjustment factor to be applied to the IMBA-derived thorium intake to meet or exceed those that would be derived using DCAL. In section 7.1, NIOSH presents plots of chest burdens versus time after acute exposure for the exact (DCAL) method, approximate (IMBA) method, and the approximate method adjusted by a factor of equal to or greater than unity, such as 1.1. The guidance derived from the results of this analysis is presented in section 7.1.3 and summarized in attachment C of OTIB-0076. Section 7.1.3, page 30, states:

> 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.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs for section 7.1 to verify the recommendations in section 7.1.3 of OTIB-0076. SC&A concurs with the recommendation and had no findings in this section but did have one observation.

Observation 6: Text runoff of plots

SC&A found that some of the vertical text in the plots in OTIB-0076 occasionally runs off the top of the plot and some of the information is lost.

4.4.2 Chronic intakes

Section 7.2 of OTIB-0076 provides examples, using chest count data, of estimating thorium intakes for chronic exposures using the IMBA program to derive IRFs and then compares them to the approximated chronic IRFs derived by using DCAL for absorption type M and S thorium. (Although DCAL can only directly derive IRFs for acute intakes, attachment B of OTIB-0076 provides details of how DCAL can be used to approximate chronic IRFs.) From this comparison, NIOSH develops an adjustment factor to be applied to the IMBA-derived thorium intake to meet or exceed those that would be derived using DCAL. In section 7.2, NIOSH presents plots of chest burdens versus time after chronic exposure for the exact (DCAL) method, approximate (IMBA) method, and the approximate method adjusted by a factor of equal to or greater than

unity, such as 1.1. The guidance derived from the results of this analysis is presented in section 7.2.2 and summarized in attachment C of OTIB-0076. Section 7.2.2, page 35, states:

> 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 $\underline{^{228}\text{Th}}$. Divide this estimated ^{228}Th intake rate by the ^{228}Th:^{232}Th ratio of 0.19:1 to obtain the $\underline{^{232}\text{Th}}$ intake rate. For chronic intakes longer than 1 year these approximate intakes will not underestimate the intakes that would be calculated with exact methods.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs for section 7.2 to verify the recommendations in section 7.2.2 of OTIB-0076. SC&A concurs with the recommendation and had no findings or observations in this section.

4.5 SC&A's evaluation of using IMBA for whole-body counts

Section 8.0 of OTIB-0076 provides methods and adjustment factors for estimating thorium acute intakes (section 8.1) and chronic intakes (section 8.2) from WBCs using the IMBA program.

4.5.1 Acute intakes

Section 8.1 of OTIB-0076 (1) provides examples, using WBC data, of estimating thorium intakes for acute exposures using the IMBA program to derive IRFs and then (2) compares them to the IRFs derived by using DCAL for absorption type M and S thorium. From this comparison, NIOSH develops an adjustment factor to be applied to the IMBA-derived thorium intakes to meet or exceed those that would be derived using DCAL. In section 8.1, NIOSH presents plots of chest burdens versus time after acute exposure for the exact (DCAL) method, approximate (IMBA) method, and the approximate method adjusted by a factor of equal to or greater than unity, such as 1.5 for type M and 1.2 for type S thorium. The guidance derived from the results of this analysis is presented in section 8.1.3 (and summarized in attachment C) of OTIB-0076, which states (p. 40):

> 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 $\underline{^{228}\text{Th}}$. Divide this estimated ^{228}Th intake by the ^{228}Th:^{232}Th ratio of 0.19:1 to obtain the $\underline{^{232}\text{Th}}$ 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.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs for section 8.1 to verify the recommendations in section 8.1.3 of OTIB-0076. SC&A concurs with the recommendations and had no findings or observations on this section.

4.5.2 Chronic intakes

Section 8.2 of OTIB-0076 (1) provides examples, using WBC data, of deriving thorium intakes for chronic exposures using the IMBA program to derive IRFs and then (2) compares them to the

approximated chronic IRFs derived by using DCAL for absorption type M and S thorium. From this comparison, NIOSH develops an adjustment factor to be applied to the IMBA-derived thorium intakes to meet or exceed those that would be derived using DCAL. In section 8.2, NIOSH presents plots of Pb-212 WBC data versus time after chronic exposure for the exact (DCAL) method, approximate (IMBA) method, and the approximate method adjusted by a factor of equal to or greater than unity, such as 1.2. The guidance derived from the results of this analysis is presented in section 8.2.2 (and summarized in attachment C) of OTIB-0076, which states (p. 43):

> 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.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs for section 8.2 to verify the recommendations in section 8.2.2 of OTIB-0076. SC&A concurs with the recommendations and had no findings or observations on this section.

4.6 SC&A's evaluation of using IMBA for total thorium in urine

Section 9.0 of OTIB-0076 provides methods and adjustment factors for estimating thorium acute intakes (section 9.1) and chronic intakes (section 9.2) from total thorium urinalysis data using the IMBA program.

4.6.1 Acute intakes

Section 9.1 of OTIB-0076 (1) provides examples, using total thorium urinalysis data, of deriving thorium intakes for acute exposures using the IMBA program to derive IRFs and then (2) compares them to the IRFs derived by using DCAL for absorption type M and S thorium. In section 9.1, NIOSH presents plots of total thorium in urine versus time after acute exposure for the exact (DCAL) method, the approximate (using IMBA or IMBA with Approximation A) method, or for the IMBA plus the Approximation A and B method. Section 9.1 introduces three approximations:

- Approximation A (p. 46; equation (9-2)): $q_{thth232}\,(t) = 0$. This simplification indicates that the ingrowth of Th-228 from Th-232 is negligible during exposure time and from end of exposure to bioassay date.

- Approximation B (p. 48; equation (9-11)): $q_{th228}\,(t) = q_{232}\,(t)$. This simplification indicates that the amount of Th-228 in the urine is approximately the same as the amount of Th-232 in the urine. However, for triple-separated thorium, the approximated urine content, $q''(t)$, equals $q_{th232}(t)$ + 0.19 multiplied by $q_{th232}(t)$ (equation (9-12)); refer to observation 6 of this report.

- Approximation C (p. 49; equation (9-15)): 1.15 divided by 1.19 then multiplied by the total intake (l_{th232}) approximately equals to l_{th232}. This approximation indicates that 1.15 divided by 1.19 is approximately equal to unity.

The information in section 9.1 indicates that an adjustment factor (e.g., 1.2 or 1.5) is not needed if Approximations A, B, and C are applied. Approximation C is not mentioned further in OTIB-0076; it was only given as a reasonable assumption NIOSH made. SC&A has one observation concerning equation (9-11), Approximation B.

Observation 7: Apparent error in equation (9-11)

OTIB-0076, page 48, states:

> 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 [emphasis added]:
>
> $$q_{th228}(t) = q_{th232}(t) \qquad \{\text{Approximation B}\} \qquad (9\text{-}11)$$

This indicates that the amounts of Th-228 and Th-232 in the 24-hour urine sample are equal. But note that $q_{th228}(t)$ is the *amount* of Th-228 in the urine, not the *urinary excretion function*, and for triple-separated thorium, the Th-228:Th-232 ratio is 0.19. Therefore, it would be appropriate to state that the thorium IRF multiplied by the thorium urine excretion rate is equal for Th-228 and Th-232. (OTIB-0076 uses the symbol *m* to represent the thorium IRF multiplied by the thorium urine excretion rate.) Therefore, equation (9-11) should actually be written as follows:

$$m_{th228}(t) = m_{th232}(t)$$

This equation is correct because the amount of thorium in the urine sample is dependent upon the intake of each of the thorium radioisotope, which in equation (9-11) consisted of a Th-228:Th-232 ratio of 0.19 for triple-separated thorium.

The guidance derived from the results of this analysis is presented in section 9.1.3 (and summarized in attachment C) of OTIB-0076, which states (p. 49):

> 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.

SC&A evaluated the methodology, approximations, and examples and ran the appropriate IMBA programs for section 9.1 to verify the recommendations in section 9.1.3 of OTIB-0076. SC&A concurs with the recommendations and had no findings and one observation.

4.6.2 Chronic intakes

Section 9.2 of OTIB-0076 (1) provides examples, using total thorium urinalysis data, of deriving thorium intakes for chronic exposures using the IMBA program to derive IRFs and then (2)

compares them to the IRFs derived by using DCAL for absorption types M and S thorium. In section 9.2, NIOSH presents plots of total thorium in urine versus time after chronic exposure for the exact (DCAL) method, the approximate (using IMBA or IMBA with approximation A) method, or for the IMBA plus the approximation A and B method. The guidance derived from the results of this analysis is presented in section 9.2.1, page 53 (and summarized in attachment C), of OTIB-0076, which states:

> 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.

SC&A evaluated the methodology and examples and ran the appropriate IMBA programs for section 9.2 to verify the recommendations in section 9.2.1 of OTIB-0076. SC&A concurs with the recommendation and had no findings or observations in this section.

4.7 SC&A's evaluation of using IMBA for thorium-228 in urine

OTIB-0076, section 10.0, provides methods and the use of adjustment factors for estimating thorium acute intakes (section 10.1) and chronic intakes (section 10.2) from Th-228 urinalysis using the IMBA program.

4.7.1 Acute intakes

Section 10.1 of OTIB-0076 (1) provides examples, using Th-228 urinalysis data, of deriving thorium intakes for acute exposures using the IMBA program to derive IRFs and then (2) compares them to the IRFs derived by using DCAL for absorption type M and S thorium. In section 10.1, NIOSH presents plots of Th-228 urinalysis results versus time after acute exposure for the exact (DCAL) method, and the approximate (IMBA) method. Section 10.1 uses IMBA plus approximation A introduced in section 9.1 of ORAUT-0076 for the analysis of Th-228 urinalysis data. Section 10.1 indicates that an adjustment factor (e.g., 1.2 or 1.5) is not needed if the appropriate approximation is applied.

The guidance derived from the results of this analysis is presented in section 10.1.2, page 57 (and summarized in attachment C), of OTIB-0076, which states:

> 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 $\underline{^{228}\text{Th}}$. Divide this estimated ^{228}Th intake by the ^{228}Th:^{232}Th ratio of 0.19:1 to obtain the $\underline{^{232}\text{Th}}$ intake. These approximate intakes will not underestimate the intakes that would be calculated with exact methods.

SC&A evaluated the methodology, use of approximation, and examples and ran the appropriate IMBA programs for section 10.1 to verify the recommendations in section 10.1.2 of OTIB-0076. SC&A concurs with the recommendation and had no findings or observations.

4.7.2 Chronic intakes

Section 10.2 of OTIB-0076 (1) provides examples, using Th-228 urinalysis data, of deriving thorium intakes for chronic exposures using the IMBA program to derive IRFs and then (2) compares them to the IRFs derived by using DCAL for absorption type M and S thorium. In section 10.2, NIOSH presents plots of Th-228 in urine versus time after acute exposure for the exact (DCAL) method, and the approximate (IMBA) method. Section 10.2 uses the Approximation A introduced in section 9.1 of ORAUT-0076 for the analysis of Th-228 urinalysis data. The guidance derived from the results of this analysis is presented in section 10.2.1, page 59 (and summarized in attachment C), of OTIB-0076, which states:

> 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 $\underline{^{228}\text{Th}}$. Divide this estimated ^{228}Th intake rate by the ^{228}Th:232Th ratio of 0.19:1 to obtain the $\underline{^{232}\text{Th}}$ intake rate. These approximate intake rates will not underestimate the intake rates that would be calculated with exact methods.

SC&A evaluated the methodology, use of approximation, and examples and ran the appropriate IMBA programs for section 10.2 to verify the recommendations in section 10.2.1 of OTIB-0076. SC&A concurs with the recommendation and had no findings or observations in this section.

5 SC&A's Evaluation of ORAUT-OTIB-0076 Attachments

OTIB-0076 has three attachments that provide detailed analysis of (A) standard thorium mixtures (i.e., first, second, and third chemical separation of thorium compounds), (B) obtaining chronic IRFs from acute IRFs, and (C) a summary of guidance for assessing thorium intakes from bioassays.

5.1 Attachment A: Standard thorium mixtures

Attachment A of OTIB-0076 provides detailed analysis of the standard thorium mixtures resulting from the chemical separation of thorium compounds at U.S. Department of Energy (DOE) sites. Thorium compounds that have not been separated contain the radionuclides, as summarized in figure 1 of this report, in equilibrium; i.e., the concentration ratios remain constant. However, when thorium compounds undergo chemical processing (such as at a DOE site), the thorium radioisotopes (Th-228 and Th-232) are separated from the other radionuclides to create nearly pure thorium. Th-228 and Th-232 continue to decay, and the other radionuclides in the thorium decay chain begin to accumulate and themselves decay (following the decay chain as shown in figure 1 of this report) but are no longer in equilibrium. Thorium chemical separation can be performed once, twice, or three times, as summarized in table A-1 of ORAUT-0076. Because Th-232 has a half-life of 1.4E10 years, its radioactivity is considered to remain constant, while the concentration of the other radionuclides in the decay chain change. To optimize the thorium content, DOE sites generally perform the separations as follows:

- At the end of the first separation (e.g., time zero), mainly Th-232 and Th-228 radionuclides are present; the Th-228:Th-232 activity ratio is 1:1. But the Th-228 begins to decay and reaches a minimum in 4.55 years and then starts to build back up (refer to figure A-1 of ORAUT-0076). The Th-228:Th-232 ratio at 4.55 years would be 0.422. Ra-

224, with a half-life of 2.6 days, follows its parent, Th-228, but Ra-228, with a half-life of 5.75 years, must build back in from Th-232 (refer to figure A-2 of ORAUT-0076).

- If a second separation is performed at 4.55 years, the Th-228 radioactivity will start to decline and reach a minimum in 2.54 years (refer to figure A-3 of ORAUT-0076). The Th-228:Th-232 ratio at this time (4.55 years plus 2.54 years equals 7.09 years) would be 0.26.

- If a third separation is performed at 7.09 years, the Th-228 radioactivity will start to decline and reach a minimum in 1.75 years (refer to figure A-5 of ORAUT-0076). The Th-228:Th-232 ratio at this time (4.55 years plus 2.54 years plus 1.75 years equals 8.84 years) would be 0.19.

The relative activities of the radioisotopes in the thorium decay chain are important to accurately evaluate a bioassay result (such as a Pb-12 or Ac-228 chest count, WBC, or thorium in urine) in terms of an intake of thorium. The minimum Th-228:Th-232 ratio could be 0.422, 0.26, or 0.19, for one, two, or three separations, respectively. If the relative concentrations are uncertain or unknown, OTIB-0076 recommends using a claimant-favorable Th-228:Th-232 ratio of 0.19 because this would provide a conservative estimate of thorium intake.

SC&A evaluated the figures, tables, and recommendations in attachment A of ORAUT-0076 and had no findings but did have one observation.

Observation 8: Clarification of assumption of constant activity

Attachment A of OTIB-0076, page 66, states.

> 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.

SC&A interprets this to means that this is a simplifying assumption and not technically correct, as illustrated in figures A-1 through A-6 and tables A-1 and A-2 of OTIB-0076, which all indicate changing radioisotope activities as a function of time.

5.2 Attachment B: Obtaining chronic intake IRFs from acute intake IRFs

DCAL can only be used to derive acute IRFs, not chronic IRFs. Therefore, NIOSH provides a method of deriving chronic IRFs from acute IRFs in attachment B of OTIB-0076.[1]

NIOSH used the standard exponential decay equation in analyzing both acute and chronic intakes in OTIB-0076. The standard exponential decay equation can be used to calculate the remaining activity at time t, $A(t)$, after the original activity, $A(0)$, has decayed by the effective half life, t_{eff}, as follows:

$$A(t) = A(0) \times \exp^{-\left[\frac{\ln(2)}{teff}\right] \times t} \qquad (1)$$

Where exp is the natural logarithm with a base of 2.7183 raised to a number and ln is the natural logarithm of a number.

The whole-body content of a chronically inhaled radioisotope at the time of bioassay is dependent on two functions:

1. the intake rate (i) (e.g., becquerel per day (Bq/d)), during a length of the chronic intake period (T)

2. the removal of the radioisotope by biological kinetics and radioactive decay that takes place during the exposure period plus the latent period (time between the end of exposure until the bioassay is performed)

OTIB-0076, pages 68–71, shows how these two functions can be addressed when determining thorium intakes by using a convolution integral.[2]

SC&A evaluated the methodology, equations, and examples provided in attachment B of OTIB-0076. A summary of NIOSH's methods and SC&A's evaluation follows.

5.2.1 Analysis of an acute intake

NIOSH started the analysis by using a hypothetical acute inhalation take of a radioisotope with a t_{eff} of 10 days, as provided on page 68 and in equation B-1 of OTIB-0076. This example illustrates the derivation an acute IRF as a function of time, represented by the symbol $m(t)$.

$$m(t) = \exp[-(\ln(2)/(10\text{d})) \times t] \qquad \text{(B-1)}$$

The acute IRF value is shown as a function of time, from zero to 30 days, in figure B-1 of OTIB-0076, which indicates that the IRF is 0.18 at time equals 25 days; e.g., for an acute intake of 1.0 Bq, the body content would be 0.18 Bq at time equal to 25 days after intake. This was a

[1] SC&A noted that the title of attachment B is "Obtaining Chronic Intake IRFs from Acute Intake IRFs"; this title contains a redundant use of the word "intake" because IRF is defined as "intake retention fraction." This occurs throughout attachment B and at the bottom of page 22 in section 5.0.

[2] A convolution integral produces a product of two functions after one is reflected about the y-axis and shifted and evaluated for all values of the shift.

simplified example using a latent time period of only 25 days, whereas the recommendations in OTIB-0076 for an acute intake are for latent periods more than 30 days.

SC&A evaluated equation B-1, figure B-1, and equation B-2 of OTIB-0076 and find them correct. However, SC&A did have the following observation.

Observation 9: Inhalation versus bloodstream uptake

Attachment B (page 68) of OTIB-0076 states: "an acute instantaneous uptake to the bloodstream is described by the following equation." However, according to the contents of the paragraph, it would appear that it should state: "an acute instantaneous uptake by inhalation is described by the following equation," because it may take some time for the inhaled material to reach the blood stream. This does not impact the objective or results of attachment B of OTIB-0076.

5.2.2 Analysis of a chronic intake

NIOSH continued the analysis by using an example and deriving a method of obtaining an approximate IRF value (for which the symbol $\widetilde{m}$ is used in the equations) for a chronic intake using acute IRFs. Figure B-2 of OTIB-0076 shows a plot of the whole-body content as a function of time for a chronic take and illustrates the interaction of the two functions of (1) intake and (2) decay/removal as discussed in section 5.2 of this report.

NIOSH used a convolution integral ($\int$) to solve for the $\widetilde{m}$ value of 0.3108667 (equation (B-12) from an example intake as detailed in the text and equations B-3 through B-12 (pages 69–71) with the associated variables as shown on page 69 of OTIB-0076:

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

OTIB-0076 equation B-12 states:

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

SC&A used the general rule for evaluation of definite integrals to verify NIOSH's results of the example of the derivation of the $\widetilde{m}$ value of 0.3108667:

$$\int \exp[\text{ax}]\, dx = \frac{\exp[\text{ax}]}{\text{a}} + \text{constant} \qquad (2)$$

SC&A then solved the integral from the lower limit to the upper limit (with the term "a" equal to a negative ln(2) divided by 10 days, which equals −0.693 divided by 10 days, which equals −0.0693 per day (d)) as follows:

$$\frac{\exp[-0.0693 \times 25\text{d}\,]}{-0.0693/\text{d}} - \frac{\exp[-0.0693 \times 10\text{d}]}{-0.0693/\text{d}} \qquad (3)$$

This resulted in:

$$(0.1768 - 0.5000)/(-0.0693/\text{d}) = (-0.3232)/(-0.0693/\text{d}) = 4.663\ \text{d}$$

And:

$$\tilde{m}(10\text{d}, 25\text{d}) = \left[\frac{1}{15\text{d}}\right] \times 4.663\text{d} = 0.31087$$

SC&A's results concur with equation B-12 of OTIB-0076. However, SC&A had an observation.

Observation 10: Rewording of statement concerning summing small intakes

Attachment B (page 69) of OTIB-0076 states: "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." However, this statement appears incorrect in that it should read: "Summing up all the infinitesimally small intakes multiplied by their respective IRFs from time 0 days to time *T* days gives the content of the whole-body at *t* days resulting from the chronic intake."

SC&A evaluated the methodology, equations, and examples provided in attachment B of OTIB-0076 and identified no findings but had the two observations described in this section.

5.3 Attachment C: Summary of guidance for assessing thorium intakes from bioassay

The purpose of OTIB-0076 is to provide correction factors for estimating Th-232 and Th-228 intakes from Pb-212 chest counts, Pb-212 WBCs, total thorium urinalysis, or Th-228 urinalysis for a chronic intake of greater than 1 year or an acute intake more than 30 days before the bioassay. Attachment C of OTIB-0076 summarizes the recommended correction factors for triple-separated thorium, which is a claimant-favorable assumption in the absence of more specific information. If the details of thorium processing are known at a site, these should be used. The methods presented in OTIB-0076 can be used for overestimating doses only, not for best estimate DRs. Approximate methods are not available for Ac-228 chest counts; such cases must be evaluated using DCAL.

SC&A evaluated the recommendations in attachment C of OTIB-0076 and found them to accurately reflect the methodology and results developed in OTIB-0076. SC&A found the summary provided in Attachment C of OTIB-0076 to be useful for the dose reconstructor and did not have any findings or observations.

6 Application of ORAUT-OTIB-0076

Section 6.0 of OTIB-0076 summarizes the appropriate use of IMBA for deriving thorium intakes as follows (p. 25):

- "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."

- "Efficiency methods using IMBA are not provided for ^{228}Ac chest counts . . . , which should be evaluated with DCAL."

- "These adjustments [applied to IMBA] 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)."

- "IMBA **cannot be used** for best estimates of intake and dose, which require the use of DCAL" (emphasis added).

7 Summary and Conclusions

SC&A reviewed OTIB-0076 and found that its methods and recommendations provide a reasonable estimate, or overestimate, of thorium intakes under a variety of conditions and bioassay methods. Attachment C of OTIB-0076 provides a helpful summary of recommendations for the dose reconstructor to use for a complex subject. SC&A has no findings but did have the following observations:

- Observation 1: Multiple definitions of intake retention fraction
- Observation 2: Multiple meanings of units
- Observation 3: Suggested rewording in section 2.1
- Observation 4: Suggested clarification in section 3.1
- Observation 5: Figure 4-3 missing
- Observation 6: Text runoff of plots
- Observation 7: Apparent error in equation (9-11)
- Observation 8: Clarification of assumption of constant activity
- Observation 9: Inhalation versus bloodstream uptake
- Observation 10: Rewording of statement concerning summing small intakes

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Appendix A: Dose and Risk Calculation software

To provide the reader with a general understanding of the DCAL software, SC&A has included portions of the abstract and overview to the DCAL manual.

Extracted portions of abstract to the DCAL manual (EPA, 2006, PDF p. 9) describe the software as follows:

> This report serves as a user's manual for the first release of the Dose and Risk Calculation software, DCAL. DCAL consists of a series of computational modules, driven in either an interactive or a batch mode, for the computation of dose and risk coefficients. The system includes extensive libraries of biokinetic and dosimetric data and models representing the current state of the art. DCAL has unique capability for addressing intakes of radionuclides by non-adults.

The manual's overview of the DCAL system is as follows (EPA, 2006, PDF p. 10):

> Under the sponsorship of the U.S. Environmental Protection Agency (EPA), the Dosimetry Research Group (now the Biosystems Modeling Team in the Advanced Biomedical Science and Technology Group) at Oak Ridge National Laboratory (ORNL) has developed a comprehensive software system for the calculation of tissue dose and subsequent health risk from intakes of radionuclides or exposure to radionuclides present in environmental media. This system serves EPA's current needs in radiation dosimetry and risk analysis. The Dose and Risk Calculation software, called DCAL, has been used in the development of two federal guidance reports (*Federal Guidance Reports 12 and 13*) (. . .) and several publications of the International Commission on Radiological Protection (ICRP), specifically in the computation of age-specific dose coefficients for members of the public (. . .).