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PUBLICATION RECORD

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03/02/2026	00	New document to provide guidance on assessing aged triple-separated thorium exposure using lead-212 (Pb-212) lung burden measured by chest counts. Incorporates formal internal and NIOSH review comments. Training is not required. Initiated by Wade C. Morris and authored by Mutty M. Sharfi.

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ACRONYMS AND ABBREVIATIONS

AWE	Atomic Weapons Employer
d	day
DCAL	Dose and Risk Calculation software
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
M	moderate (absorption type)
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
S	slow (absorption type)
SRDB Ref ID	Site Research Database Reference Identification (number)
TIB	technical information bulletin
U.S.C.	*United States Code*
§	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), such as changing scientific understanding of operations, processes, or procedures involving radioactive materials. TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a U.S. Department of Energy (DOE) or Atomic Weapons Employer (AWE) facility. It does not mean, nor should it be equated to, an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in 42 *United States Code* (U.S.C.) § 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000, respectively.

2.0 PURPOSE

For the purpose of this TIB, aged triple-separated thorium is defined as thorium that has started out as purified thorium (i.e., the nonthorium progeny was chemically removed via three separation efforts) and then aged over time, thus allowing the thorium progeny to grow back. This TIB provides guidance for assessing aged triple-separated thorium exposure using the Pb-212 lung burden measured by chest counts. This includes:

- The amount of thorium progeny that grows in over time,
- The key radionuclides that should be included in the intake and dose assessment, and
- The basis for using the thorium-228 (Th-228) biokinetic model in the Integrated Modules for Bioassay Analysis [IMBA; James et al. 2005] to overestimate the Th-228 intake from aged triple separated thorium following guidance in ORAUT-OTIB-0076, *Guiding Reconstruction of Intakes of Thorium Resulting from Nuclear Weapons Programs* [OTIB-0076; Oak Ridge Associated Universities (ORAU) Team (ORAUT) 2014].

The R code is provided in ORAUT [2026].

3.0 THORIUM DECAY CHAIN

Thorium is a naturally occurring radioactive metal discovered in 1828. The thorium-232 (Th-232) isotope of thorium is the parent of a 12-member decay chain that ends with stable lead-208 (Pb-208). Figure 3-1 shows the members of the decay chain.

The ratio of the activities of Th-228 to Th-232 is 1:1 for natural thorium that has been undisturbed for many decades (e.g., thorium ore in the ground). If the thorium is chemically processed, the thorium isotopic ratio is temporarily perturbed because the radium-228 (Ra-228) and actinium-228 (Ac-228) progenies are removed (Th-228 and Th-232 are chemically identical). Depending on the details of the chemical processing, the ratio can be as low as 0.19:1 but will eventually return to 1:1 [ORAUT 2014].

To assess the thorium intakes via in vivo chest count data, the thorium isotopic ratio is needed because the Th-232 lung burden cannot be observed directly. It is estimated using the Th-228/Th-232 ratio of the inhaled material and assuming the Th-228 burden is equal to the measured Pb-212 activity. In OTIB-0076, triple-separated thorium was presented as a mixture of Th-232 and Th-228. Triple-separated thorium was intended for use during periods at a site when freshly separated thorium with non-natural ratios of the daughter products could be encountered. When thorium separation activities at a site cease and the material is aging, the long-lived progenies of Th-232 (Ra-228 and Th-228) begin to grow in and approach secular equilibrium with the Th-232 parent over the course of a few decades.

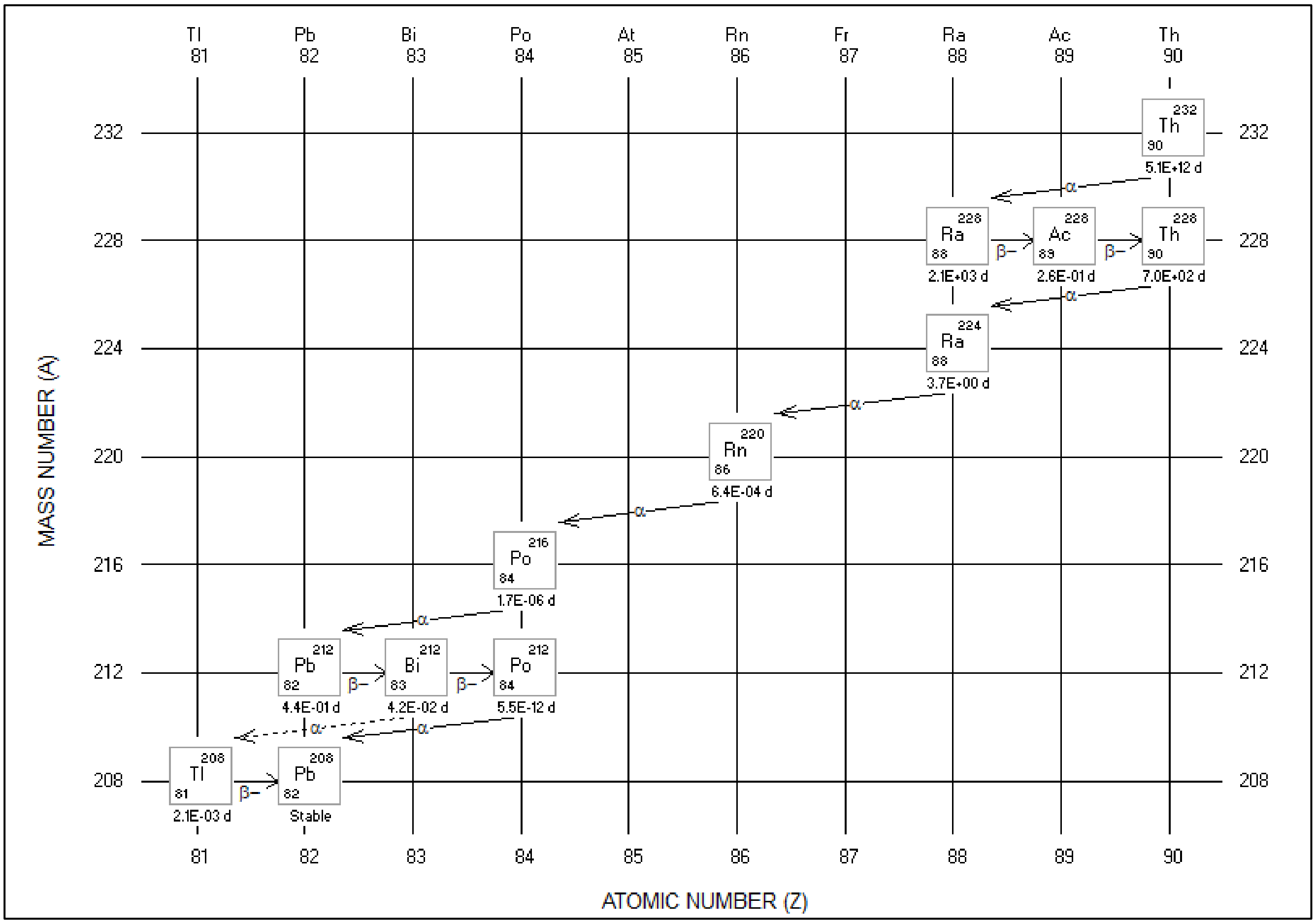

Figure 3-1. Th-232 decay chain (IMBA). Attachment A contains an extended description. Source: James et al. [2005].

In this paper, the decay parameters for Th-232 and its progeny are used to model the ingrowth curves for various times. These models account for the aging of the triple-separated thorium and the ingrowth of the progeny that were previously removed. Therefore, the isotopic ratios from these aged models are more realistic than the fresh models for times after thorium separation.

4.0 INGROWTH CURVES

The decay of a parent nuclide and ingrowth of its progenies are governed by first-order kinetics equations. The Bateman equation, Equation 4-1, can be used for calculating the amount of activity over time [Bateman 1910]:

$$A_n(t) = \lambda_n N_n(t) = \lambda_n \left[N_1(0) x \left(\prod_{i=1}^{n-1} \lambda_i \right) \sum_{i=1}^{n} \frac{\exp(-\lambda_i t)}{\prod_{j=1, j \neq i}^{n} \left(\lambda_j - \lambda_i \right)} \right] \tag{4-1}$$

Attachment A contains an extended description.

where

1	is	the parent
n	is	the n-th progeny
A	is	activity
N	is	the number of atoms
λ	is	the decay constant
t	is	time

This approach can then be continued through the entire decay chain given the initial conditions of triple-separated thorium and the half-lives of each of the progeny. Doing this results in the ratios in Table 4-1.

It is recommended that implementation of aged triple-separated thorium material be performed in a consistent manner as the approach used for aged plutonium mixtures. Therefore, the following brackets are recommended as an efficiency method for the implementation of triple-separated aged progeny ratios as a function of time on intake assessment from Pb-212 lung burdens:

- Years 0 to 4: assume fresh material.
- Years 5 to 9: assume 5-year aged material.
- Years 10 to 19: assume 10-year aged material.
- Years 20 or more: assume 20-year aged material.

Earliest values for the ranges were chosen because fresher material results in a more favorable intake assessment.

Table 4-1. Ratios of progeny to Th-232 as a function of time for triple-separated thorium.[a,b]

Days	Years	Th-232	Ra-228	Ac-228	Th-228	Ra-224	Rn-220[c]	Pb-212	Bi-212[d]	Tl-208	Total gross alpha[e]
0	0	1	0	0	0.19	0	0	0	0	0	1.19
365	1	1	0.11349	0.11338	0.15087	0.15107	0.15107	0.15110	0.15110	0.05431	1.75518
730	2	1	0.21410	0.21401	0.15599	0.15570	0.15570	0.15566	0.15566	0.05594	1.77874
1,095	3	1	0.30330	0.30321	0.18825	0.18766	0.18766	0.18759	0.18758	0.06742	1.93881
1,460	4	1	0.38237	0.38229	0.23615	0.23539	0.23539	0.23530	0.23529	0.08456	2.17762
1,825	5	1	0.45246	0.45240	0.29205	0.29122	0.29122	0.29111	0.29110	0.10462	2.45680
2,190	6	1	0.51460	0.51454	0.35095	0.35011	0.35011	0.35000	0.34999	0.12579	2.75126
2,555	7	1	0.56969	0.56964	0.40969	0.40886	0.40886	0.40876	0.40875	0.14690	3.04502
2,920	8	1	0.61853	0.61848	0.46629	0.46550	0.46550	0.46541	0.46540	0.16726	3.32820
3,285	9	1	0.66182	0.66178	0.51963	0.51889	0.51889	0.51880	0.51879	0.18645	3.59509
3,650	10	1	0.70020	0.70017	0.56911	0.56843	0.56843	0.56835	0.56834	0.20426	3.84274
4,015	11	1	0.73423	0.73419	0.61450	0.61388	0.61388	0.61381	0.61380	0.22060	4.06996
4,380	12	1	0.76439	0.76436	0.65581	0.65525	0.65525	0.65518	0.65517	0.23547	4.27674
4,745	13	1	0.79113	0.79110	0.69318	0.69267	0.69267	0.69261	0.69260	0.24892	4.46378
5,110	14	1	0.81483	0.81481	0.72681	0.72636	0.72636	0.72630	0.72630	0.26103	4.63218
5,475	15	1	0.83585	0.83583	0.75699	0.75659	0.75659	0.75654	0.75653	0.27190	4.78328
5,840	16	1	0.85448	0.85446	0.78400	0.78363	0.78363	0.78359	0.78359	0.28162	4.91849
6,205	17	1	0.87099	0.87098	0.80811	0.80779	0.80779	0.80775	0.80774	0.29030	5.03923
6,570	18	1	0.88564	0.88562	0.82961	0.82932	0.82932	0.82929	0.82928	0.29804	5.14687
6,935	19	1	0.89862	0.89860	0.84876	0.84850	0.84850	0.84847	0.84846	0.30494	5.24272
7,300	20	1	0.91012	0.91011	0.86579	0.86556	0.86556	0.86553	0.86553	0.31107	5.32799
7,665	21	1	0.92032	0.92031	0.88093	0.88072	0.88072	0.88070	0.88069	0.31652	5.40378
8,030	22	1	0.92936	0.92936	0.89437	0.89419	0.89419	0.89417	0.89417	0.32136	5.47112
8,395	23	1	0.93738	0.93737	0.90632	0.90616	0.90616	0.90614	0.90613	0.32566	5.53092
8,760	24	1	0.94449	0.94448	0.91692	0.91677	0.91677	0.91676	0.91676	0.32948	5.58400
9,125	25	1	0.95079	0.95078	0.92632	0.92620	0.92620	0.92618	0.92618	0.33287	5.63110

a. Source: ORAUT [2025, 2026].

b. Ra-224 – radium-224; Rn-220 – radon-220; Bi-212 – bismuth-212; Tl-208 – thallium-208.

c. Assume polonium-216 (Po-216) progeny is in secular equilibrium with its parent Rn-220.

d. Assume polonium-212 (Po-212) progeny is in secular equilibrium with its parent Bi-212.

e. The values in the total gross alpha column are the sum of the activity fractions for all alpha emitters. Note, Po-216 and Po-212 are not included in the table due to their ultra short half-life. However, these two radionuclides are alpha emitters and therefore are included.

5.0 RADIONUCLIDES TO BE INCLUDED IN AN ASSESSMENT

As noted in Section 3.0, there are 12 radionuclides in the Th-232 decay chain. However, because of the difference in decay constants, most of these radionuclides contribute less than 0.1% to the Th-232 intake or dose assessment.

5.1 INTAKE ASSESSMENTS

Th-232 intake assessments are performed using the chest count results for Pb-212 and assumptions that relate the Pb-212 lung burden to the intake of Th-232 and its progeny. The Pb-212 lung burden $q(t)$ at time t after the intake is calculated as follows:

$$q(t) = \sum_{X=Th232}^{Pb212} I_X \, m_{PbX}(t) \quad (5\text{-}1)$$

where

I	is	intake of the specific radionuclide X
$m_{PbX}(t)$	is	intake retention fraction for the Pb-212 lung burden at time t for radionuclide X

Below is a list of the Th-232 progeny that eventually decay into Pb-212 [James et al. 2005]:

1. Th-232 (half-life is 1.405E10 years),
2. Ra-228 (half-life is 5.75 years),
3. Ac-228 (half-life is 6.15 hours),
4. Th-228 (half-life is 1.9116 years),
5. Ra-224 (half-life is 3.66 days),
6. Rn-220 (half-life is 55.6 seconds), and
7. Po-216 (half-life is 0.145 second).

Only three of these (Th-232, Ra-228, and Th-228) have half-lives greater than a year. Therefore, an initial intake of these radionuclides continues to have a measurable contribution to the measured Pb-212 activity for many years after the initial intake.

NOTE: When referring to the initial intake ratio this refers to the progeny ratio at the time of intake, not the contribution of each progeny that is changing over time as the material is in the lung.

Ac-228 and Ra-224 have half-lives on the order of hours to days. Though the initial activity decays away, they could be present long enough to have a measurable contribution to the Pb-212 activity for a day or two to possibly a couple of weeks after intake.

Rn-220 and Po-216 have half-lives less than a minute. The intake of these radionuclides quickly decays and therefore would not have a measurable contribution to the Pb-212 activity after the initial intake.

Tables 5-1 and 5-2 indicate the estimated contribution of Pb-212 lung burden after an acute intake of Types M and S natural thorium (i.e., in full equilibrium), respectively. Natural thorium was used to maximize the contribution of the progeny. Depending on the timing of the chest count, the only radionuclides that significantly contribute to the Pb-212 lung burden are Th-232, Ra-228, Th-228, and Ra-224. Therefore, when performing an intake analysis for an aged triple-separated thorium mixture, only Th-232, Ra-228, Th-228, and Ra-224 need to be included in the intake retention fraction estimates for Pb-212 lung burdens. The other short-lived radionuclides do not contribute significantly to the expected Pb-212 lung burden and therefore need not be included.

Table 5-1. Contribution of progeny to the Pb-212 activity in the lung after a Type M natural thorium mixture acute intake.[a]

Days after intake	Th-232	Ra-228	Ac-228	Th-228	Ra-224
1	0.00%	0.00%	0.00%	11.03%	88.96%
2	0.00%	0.01%	0.01%	23.70%	76.28%
4	0.00%	0.07%	0.02%	46.67%	53.24%
6	0.00%	0.18%	0.02%	63.27%	36.53%
8	0.00%	0.31%	0.03%	74.66%	25.01%
10	0.00%	0.46%	0.03%	82.38%	17.13%
30	0.01%	2.32%	0.04%	97.25%	0.39%
90	0.11%	7.86%	0.03%	91.99%	0.00%
180	0.46%	15.37%	0.03%	84.14%	0.00%
365	1.80%	28.16%	0.03%	70.01%	0.00%

a. Source: ORAUT [2026].

Table 5-2. Contribution of progeny to the Pb-212 activity in the lung after a Type S natural thorium mixture acute intake.[a]

Days after intake	Th-232	Ra-228	Ac-228	Th-228	Ra-224
1	0.00%	0.00%	0.00%	12.15%	87.84%
2	0.00%	0.01%	0.01%	25.84%	74.14%
4	0.00%	0.07%	0.02%	49.77%	50.15%
6	0.00%	0.16%	0.02%	66.32%	33.49%
8	0.00%	0.28%	0.03%	77.27%	22.42%
10	0.00%	0.41%	0.03%	84.49%	15.07%
30	0.01%	1.81%	0.04%	97.84%	0.30%
90	0.11%	4.71%	0.03%	95.14%	0.00%
180	0.51%	6.30%	0.03%	93.16%	0.00%
365	2.37%	5.56%	0.03%	92.04%	0.00%

a. Source: ORAUT [2026].

5.2 DOSE ASSESSMENTS

As shown in Section 4.0, aged triple-separated thorium intakes are a mixture of short- and long-lived radionuclides. A comparison was made of the total dose from all radionuclides in an aged triple-separated thorium mixture to only considering the thorium and radium isotopes. The comparison used the committed organ dose conversion factors from International Commission on Radiological Protection (ICRP) Publication 68 for inhalation intakes [ICRP 1994]. To maximize the contributions of the thorium progeny, natural thorium was assumed (i.e., all progeny are in secular equilibrium).

Table 5-3 demonstrates that the dose associated with the thorium and radium isotopes (i.e., Th-232, Ra-228, Th-228, and Ra-224) account for at least 99% of the total dose of the thorium mixture. For mixtures that have not reached full secular equilibrium, the contribution to the total dose for nonthorium and nonradium radionuclides would be even less because the amount of short-lived progeny present would be less (see ratios in Table 4-1). Therefore, when performing a dose analysis for an aged triple-separated thorium mixture, only Th-232, Ra-228, Th-228, and Ra-224 need to be included in the dose estimates. The other radionuclides are not considered to contribute significantly to the organ dose and therefore need not be included.

Table 5-3. Contribution of thorium and radium to the total dose.[a]

Organ	Th + Ra	Organ	Th + Ra
Adrenals	99.9%	Muscle	99.9%
Urinary bladder	99.9%	Ovaries	99.9%
Bone surface	99.9%	Pancreas	99.9%
Brain	99.9%	Red Marrow	99.9%
Breast	99.9%	Extrathoracic airways	99.5%
Esophagus	99.9%	Lungs	99.9%
Stomach	99.9%	Skin	99.9%
Small intestine	99.9%	Spleen	99.9%
Upper large intestine	99.9%	Testes	99.9%
Lower large intestine	99.9%	Thymus	99.9%
Colon	99.9%	Thyroid	99.9%
Kidneys	99.6%	Uterus	99.9%
Liver	99.3%		

a. Source: ORAUT [2026].

6.0 ASSESSING AGED TRIPLE-SEPARATED THORIUM IN IMBA

Assessing aged triple-separated thorium in IMBA has two issues. First, the lung burdens are not for the primary radionuclide. The lung burdens are reported in activity of Pb-212 rather than the parent thorium. Second, as explained in ORAUT-OTIB-0060, *Internal Dose Reconstruction* [ORAUT 2018], IMBA employs shared kinetics rather than independent kinetics. This results in IMBA incorrectly calculating the annual doses for various radionuclides, specifically Th-232, Ra-228, Th-228, and Ra-224.

As an efficiency method, OTIB-0076 indicates that IMBA, with some adjustments, can be used to estimate the intake and intake rates for acute and chronic exposures of triple-separated thorium. The adjustments ensure that the intake amounts or rates do not underestimate those that would be calculated with exact methods based on the *D*ose and Risk *Cal*culation software (DCAL) [Eckerman et al. 2006]. Because OTIB-0076 only considers unaged triple-separated thorium, a similar analysis to that in OTIB-0076 was performed for aged triple-separated thorium to verify that the guidance in OTIB-0076 associated with the use of IMBA to estimate an intake amount of triple-separated thorium is also valid for aged triple-separated thorium mixtures.

Regardless of the implemented adjustments, IMBA should not be used for best estimates of intakes or dose from aged triple-separated thorium mixtures. These require the use of DCAL.

6.1 EXAMPLES OF INHALED 5-YEAR AGED TRIPLE-SEPARATED THORIUM

The following examples demonstrate that the OTIB-0076 guidance on using the IMBA thorium biokinetic model for triple-separated thorium to estimate the Th-228 intake portion can also be applied to an aged triple-separated thorium mixture.

6.1.1 Acute Intake Example

Assume an acute intake of triple-separated thorium that has aged for 5 years. The ratios for the Th-232 to Ra-228, Th-228, and Ra-224 are provided in Table 4-1, respectively. Once this thorium aerosol is inhaled, Pb-212 starts to grow in predominately from the Th-232, Ra-228, Th-228, and Ra-224. Thus the Pb-212 lung burden, Equation 5-1, for $q(t)$ at time *t* after the intake reduces to as follows:

$$q(t) = I_{\text{Th232}}\, m_{\text{PbTh232}}(t) + I_{\text{Ra228}}\, m_{\text{PbRa228}}(t) + I_{\text{Th228}}\, m_{\text{PbTh228}}(t) + I_{\text{Ra224}}\, m_{\text{PbRa224}}(t) \quad (6\text{-}1)$$

where

I	is	intake of the specific radionuclide
$m_{\text{Pb}X}(t)$	is	intake retention fraction for the Pb-212 lung burden at time *t* for radionuclide *X*

Substituting the mixture ratios from Table 4-1 into Equation 6-1 yields:

$$\begin{aligned} q(t) &= I_{\text{Th232}}\, m_{\text{PbTh232}}(t) + (0.45246 \times I_{\text{Th232}})\, m_{\text{PbRa228}}(t) \\ &+ (0.29205 \times I_{\text{Th232}})\, m_{\text{PbTh228}}(t) + (0.29122 \times I_{\text{Th232}})\, m_{\text{PbRa224}}(t) \end{aligned} \quad (6\text{-}2)$$

Attachment A contains an extended description.

Equation 6-2 can be solved for the intake approximation of Th-232:

$$I_{\text{Th232}} = \frac{q(t)}{0.292 \times m_{\text{Th228}}(t)} \quad (6\text{-}3)$$

Attachment A contains an extended description.

where

$m_{\text{Th228}}(t)$	is	intake retention fraction for the Th-228 lung burden at time *t*

An assumed 300-nCi acute intake of Th-232 associated with a 5-year-old triple-separated mixture was applied to Equation 6-2 to estimate the Pb-212 lung burden. That lung burden was then applied to Equation 6-3 which estimates the intake of Th-232 using the IMBA Th-228 biokinetic model. Table 6-1 provides the results of these estimates for 100, 365, and 1,000 days after an intake.

Table 6-1. Comparison of exact solution to IMBA approximation for an acute intake of 5-year aged triple-separated thorium.[a]

Actual intake of Th-232 (nCi)	Days after intake	Absorption type	Pb-212 lung burden[b] (nCi)	Th-228 lung burden IRF	Unadjusted Th-228 intake (nCi)	Adjusted Th-228 intake[c] (nCi)	Th-232 intake[d] (nCi)
300	100	M	1.706	1.832E–02	93.10	102.41	351
300	365	M	0.384	2.778E–03	138.14	151.95	520
300	1,000	M	0.013	3.768E–05	334.36	367.80	1,259
300	100	S	3.090	3.319E–02	93.09	102.40	351
300	365	S	2.546	1.844E–02	138.07	151.88	520
300	1,000	S	1.877	5.616E–03	334.16	367.57	1,259

a. The R code package and R code for these calculations are provided in ORAUT [2025, 2026].
b. Values are rounded to the nearest thousandth of a nCi. Calculations are based on unrounded values.
c. Section 7.1.3 of OTIB-0076 recommends multiplying the calculated Th-228 intake by a factor of 1.1.
d. The Th-228:232 ratio for 5-year-old triple-separated mixture, per Table 4-1 is 0.29205.

Table 6-1 shows that the application of the IMBA guidance in OTIB-0076 always results in an overestimate of actual intake amount of Th-232. This demonstrates that the guidance in OTIB-0076 for using IMBA to estimate an acute intake of Th-232 associated with triple-separated thorium is also valid for aged triple-separated thorium.

NOTE: Longer-aged material (e.g., 20 years) was also considered and did not affect the conclusion.

6.1.2 Chronic Intake Example

Applying the same concept from Section 6.1.1 to a chronic intake of Th-232 associated with a 5-year-old triple-separated mixture is possible by assuming a total Th-232 intake of 300 nCi over the chronic period results in the values in Table 6-2 for 100, 365, and 1,000 days after the start of the intake. The chronic intake is assumed to be constant from day zero to the estimated lung burden day (e.g., for Row 1 the intake rate is 3 nCi/d for 100 days, and for Row 2 the intake rate is 0.822 nCi/d for 365 days).

Table 6-2. Comparison of exact solution to IMBA approximation for a chronic intake of 5-year aged triple-separated thorium.[a]

Actual intake of Th-232 (nCi)	Days after intake	Absorption type	Pb-212 lung burden[b] (nCi)	Th-228 lung burden IRF[c]	Unadjusted Th-228 intake (nCi)	Adjusted Th-228 intake[d] (nCi)	Th-232 intake[e] (nCi)
300	100	M	2.698	3.220E-02	83.80	92.18	316
300	365	M	1.367	1.465E-02	93.31	102.64	351
300	1,000	M	0.568	5.749E-03	98.78	108.66	372
300	100	S	3.721	4.396E-02	84.64	93.11	319
300	365	S	3.011	2.981E-02	101.03	111.13	381
300	1,000	S	2.494	1.769E-02	140.97	155.06	531

a. The R code package and R code for these calculations are provided in ORAUT [2025, 2026].
b. Values are rounded to the nearest thousandth of a nCi. Calculations are based on unrounded values.
c. IRF is in the format of a unit total intake amount, i.e., 1 unit intake summed over the total length of the chronic intake period.
d. Section 7.2.2 of OTIB-0076 recommends multiplying the calculated Th-228 intake rate by a factor of 1.1.
e. The Th-228:232 ratio for 5-year-old triple-separated mixture, per Table 4-1 is 0.29205.

Table 6-2 shows that the application of the IMBA guidance in OTIB-0076 results in an overestimate of actual Th-232 intake amount for exposures equal to or greater than 100 days. This demonstrates that the guidance in OTIB-0076 for using IMBA to estimate a chronic intake associated with triple-separated thorium is also valid for aged triple-separated thorium chronic intakes that are longer than 365 days. Given that short-duration (i.e., less than 365 days) chronic intakes have other potential inherent issues, use of the IMBA guidance in OTIB-0076 was limited to 365 days.

NOTE: Longer-aged material (e.g., 20-year aged) was also considered and did not impact the conclusion.

7.0 CONCLUSIONS

- When no representative thorium and progeny isotopic measurements are available, the thorium progeny ratios in Table 4-1 should be used to assess the amount of activity that grows in over time.

- The only radionuclides that need be included in an intake and/or dose assessment for aged triple-separated thorium are Th-232, Ra-228, Th-228, and Ra-224.

- The guidance in OTIB-0076 on use of the Th-228 biokinetic model in IMBA as an efficiency approach to estimate the Th-228 intake amount is acceptable for assessing aged triple-separated thorium for all acute intakes and for chronic intakes longer than 365 days.

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ATTACHMENT A
EXTENDED DESCRIPTIONS OF FIGURES

This attachment contains extended descriptions for figures and equations that exceed the character limit for inline alt text. These descriptions are provided to enhance accessibility for screen reader users.

Figure 3-1
Decay chain of Th-232 into its progeny, which decays to…

- Ra-228 via alpha decay, which decays to…
- Ac-228 via beta decay, which decays to…
- Th-228 via beta decay, which decays to…
- Ra-224 via alpha decay, which decays to…
- Rn-220 via alpha decay, which decays to…
- Po-216 via alpha decay, which decays to…
- Pb-212 via alpha decay, which decays to…
- Bi-212 via beta decay, which decays to…
- Either polonium-212 via beta decay or Th-208, both of which decay to Pb-208, which is stable.

Equation 4-1
Equation showing the Bateman equation being used to estimate the activity of progeny at any given time using the exponential decay constants for each of the progeny.

A sub n at time t is equal to lambda sub n times N sub n at time t. That is equal to lambda sub n times the product, open bracket, N sub 1 at time zero times, open parenthesis, the product from i equals 1 to n minus 1 of lambda sub radionuclide i, close parenthesis, times the sum from i equals 1 to n of the fraction with a numerator of the exponential of negative lambda sub i times t, and a denominator of the product from j equals 1 to n, where j does not equal i, of lambda sub j minus lambda sub i, close bracket.

Equation 6-2
Equation showing Table 4-1 values for a 5-year aged triple-separated thorium mixture being substituted into Equation 6-1. The Ra-228 intake amount is substituted for 0.452 times the Th-232 intake amount. The Th-228 intake amount is substituted for 0.292 times the Th-232 intake amount. The Ra-224 intake amount is substituted for 0.291 times the Th-232 intake amount.

Equation 6-3
Equation showing the solution of Equation 6-2 using the assumption that the quantity of Pb-212 present that comes from the Th-232, Ra-228, and Ra-224 is negligible. This resulted in the intake approximation of the Th-232 intake amount to be equal to the total Pb-212 lung burden divided by the product of 0.292 and the Pb-212 lung burden intake retention fraction for Th-228.