White Paper: Feasibility of Thorium Dose Reconstruction

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1. Tasking

Develop a document that addresses feasibility, specifically for thorium exposures.

- *Identify the level of data and information needed to determine that reconstructing thorium exposures is feasible.*
- *Look at past SEC determinations where thorium was the reason for establishing an SEC and the amount of data and information we had for reconstructing the dose.*
- *Look at sites where the Advisory Board on Radiation and Worker Health (ABRWH) agrees with NIOSH that reconstructing thorium dose is feasible.*

2. Overview

This discussion is organized by thorium feasibility determination, including proposed methods that were not accepted, methods that are still in process or are currently in use and have not specifically been discussed with the ABRWH, and those that have been accepted explicitly or through the denial of an SEC. Some sites have periods where thorium reconstruction has been determined to be infeasible but also have periods where a methodology has been accepted or is still in development or discussion, so these sites appear in multiple categories.

A number of sites have had SEC periods established due to a complete lack of thorium data (bioassay and workplace). These sites are not addressed here as they provide no useful information for evaluation.

There is no site profile for many Atomic Weapons Employer (AWE) sites, with individual dose reconstruction (DR) methodologies developed on an as-needed based. In such cases, the observations below are based on approaches used for individual DRs for the site in question. Site information regarding thorium use was also taken from these documents.

A brief summary of thorium use at each site is included in the discussion. For sites appearing in multiple categories, this discussion is included only with the site's first appearance.

3. Methodology and Feasibility Summaries

3.1. Methods Determined to be Infeasible

These methods were determined to lack sufficient detail or to inadequately bound all possible thorium intakes at the given site.

3.1.1. Fernald

Fernald processed thorium from 1954 to 1979 and was the national thorium materials repository for the DOE starting in 1972. In 1968 the monitoring program at Fernald switched from daily weighted average exposure (DWE) monitoring (see 3.3.2 for a discussion of this earlier period) to chest counts using the Y-12 Mobile In-Vivo Radiation Monitoring Laboratory (MIVRML). Chest counts were performed with this system until 1978, with results being reported in units of mg of thorium. The mass of thorium was calculated from a sum of three ratios representing the counts in three regions of the spectrum divided by the counts in a region immediately above the respective regions. The regions correlate with a photopeak from Pb-212 and two peaks from Ac-228. Raw results from the counts were not available so the SEC (NIOSH 2006) at Fernald for this time period (1968-1978) was in large part the result of difficulties associated with trying to convert from the reported mass of thorium in the lungs to the activity of thorium and its daughters.

3.1.2. Los Alamos National Laboratory (LANL)

Several different efforts at LANL are identified as possibly involving thorium isotopes. The site profile (ORAUT 2009) cites potential airborne ^{232}Th exposure from the Sigma complex from 1944 to 1963, and notes material in the form of ingots and oxides in the Thorium Storage Building (Building 159) and air emissions results from several years indicating airborne releases of ^{232}Th from Building 66 in TA-3. Work with ^{232}Th also appears to have taken place in the 1980s. Available monitoring data consist of thirteen urine samples with isotopic thorium results reported in the 2005-2008 time frame and 1300 ^{234}Th chest counts in 2004. There are no other samples specific to thorium. ORAUT proposed to use the uranium coworker study intake rates as a surrogate for thorium intakes with the rationale that "*the radiological properties and health physics controls for natural thorium are comparable to uranium, co-worker data for uranium could similarly be used to bound intakes of natural thorium*" (NIOSH 2009a). [Note that the reference is an early version of the evaluation report, not the current published version.] This was in concert with proposed surrogates for other "exotic" nuclides at the site. The surrogate method in general was found to have inadequate justification for the LANL site for the period through 1995. The feasibility of dose reconstruction for the post-1995 period is currently under evaluation by the ORAU Team.

3.1.3. Mallinckrodt

At Mallinckrodt, pitchblende raffinate was processed to produce a concentrated thorium (Th-230) solution. There are about 70 urine samples from March and April 1955, with no other thorium-specific urinalysis. There are very few whole body counts and few general air samples, and source term information is lacking. A thorium intake assignment was included in early versions of the site profile (ORAUT 2003) but it was not comprehensive because there were gaps in the available data. The SEC (SEC-00012, -00133) was granted based on a general lack of monitoring and source term data.

3.1.4. Savannah River Site

There were five major thorium-processing campaigns conducted at SRS (ORAUT 2005a). There were 224 thorium urine samples collected in 1956; NIOSH reported that none of these were positive. For the 1953 to 1965 time frame, the use of uranium bioassay as a substitute for thorium bioassay was proposed (NIOSH 2010b). This proposal was based on the assumption that there were no detectable thorium intakes and the determination that the mass balance ratio of thorium-to-uranium would have been less than 1 to 1 based on the relative fraction of thorium-to-uranium handled at SRS. The use of a 1 to 1 mass balance was proposed to provide a bounding assumption. Chronic intakes of natural uranium were modeled using the available uranium data and annual intakes of ^{232}Th were then derived by assuming a mass equal to the natural uranium. SRS Work Group discussions (*SRS WG transcript, February 3, 2011*) led to multiple issues, including debate as to whether any of the urine samples were actually positive and that thorium was used in areas other than the location used for the analysis, so this method was subsequently withdrawn.

Chest counting was initially examined for use in assessing thorium intakes from 1965 to 1971 but records were available only in individual personnel radiological records and a complete review of these records was determined to be infeasible. Two hundred seventy individual air sample results from the 300-M area facilities were subsequently analyzed. Of these, 262 were identified as "routine" and collected using portable air pumps, while the remaining 11 samples were special impactor samples. The sampling heads of the routine samplers were extended up to face-level, with the intent that they would represent a breathing zone sample. These results were fitted to a lognormal distribution and daily intake rates were calculated from the geometric mean and the 95th percentile values (ORAUT 2010a). These data addressed only the 300 Area, so NIOSH determined that it could not estimate thorium doses from 1953 through September 1972 at other facilities where work with unencapsulated thorium was performed.

3.2. Methods/Sites Still in Discussion or Not Yet Reviewed

These methods have been proposed but are still in discussion with a Work Group or have not yet been vetted through the Advisory Board.

3.2.1. Albany Research Center

ARC is a DOE facility with no SEC period. From 1954 to 1971, the site was engaged in metallurgical operations involving thorium. Operations included reduction, melting, machining, welding, and alloying (Poppleton 1979). The site covered period begins in 1987 so this operational era is not included. Covered activities include remediation (1987-1993) and the era following remediation (1995 to present). Intakes for the latter period are derived from the highest fixed contamination area measured in on-site buildings after remediation of ARC. The most claimant-favorable radionuclide was assumed (^{232}Th, absorption Type M) based on the past history of the site (*ARC individual DR report*). The remediation era has not been addressed because there have been no claims with employment during that time.

3.2.2. Fernald

As discussed in the infeasibility section (3.1.1), the SEC currently in place at Fernald was due primarily to an inability to convert chest count results in terms of thorium mass to the activity of thorium and its daughters. This problem was effectively solved starting in 1979 when a new chest counter was used and the results reported in terms of the activity of Pb-212 and Ac-228. This time frame is still under discussion in the Work Group so it is not yet clear if the proposed method will be found adequate.

3.2.3. Hanford

There was a potential for thorium exposures at many locations throughout Hanford's history as described in the Hanford Site Description (ORAUT 2010b). For example, the processing of irradiated powdered thorium oxide targets to recover ^{233}U began in 1965. In 1970, the targets were changed to pelletized thorium oxide.

Although a thorium urinalysis procedure was in place at least as far back as 1955, there are no thorium urinalysis results in the database until 1979. Whole-body counting specific for ^{232}Th first appears in the database in the early 1960s for a few workers, with tens of counts per year in the later 1960s and a few counts in the 1970s. Th-232 was not routinely reported in whole body counts, but a prominent ^{228}Ac peak would have been noticed and investigated. If nothing was detected, no activity is included in the database. (ORAUT 2010c)

Revision 1 of the internal dosimetry coworker study (ORAUT 2007) included rationale for the assignment of the uranium intake rate as a surrogate for thorium. It stated that exposure to thorium occurred mostly in the 300 Area and was usually associated with uranium (e.g., same buildings or workers), and exposure could have occurred as early as 1950 and lasted until 1970. Although there was less thorium than uranium by mass handled at Hanford, the potential for intake could have been similar on an individual worker basis. Therefore, the same mass intake rates were assumed and the activity of ^{232}Th was determined by the ratio of specific activities of ^{232}Th and recycled uranium. The coworker study was subsequently rolled into the site profile as an appendix and canceled as a separate document; this discussion is not included in the current site profile because an SEC (SEC-00152) was designated through 1972. However, there is direction to assign intakes of thorium for a few areas using the 95th percentile of the uranium coworker distribution (ORAUT 2010c).

The class for SEC-00201, covering all areas through 1983, was recommended by the ABRWH per NIOSH recommendation (NIOSH 2012). The Work Group review of the post-SEC period starting January 1, 1984 is still underway, with no stated decision on the ability to bound or reconstruct thorium dose at Hanford post-1983 at this time. There are currently open matrix items pertaining to the assignment of thorium intakes regarding the establishment of the validity of using uranium bioassay to assign thorium intakes.

3.2.4. Pantex

Thorium at Pantex exists as thorium metal, thorium alloys, or materials impregnated with a thorium compound. Workers handled these forms during assembly and disassembly of certain weapons. There are a few thorium urine and fecal samples in 1983. Two hundred fifty eight urine samples were analyzed between 1992 and 1996 and 151 fecal samples analyzed between 1996 and 2000. The initial proposed method for 1980 through the present was to apply the same method as for plutonium, on the basis that it would be claimant favorable because there were fewer disassemblies containing thorium. It was argued that exposure to plutonium, and by extension, to thorium, would be acute rather than chronic and that the potential for intake was rare. Intake assignment was based on the criterion for incident investigation.

The current proposed method is based on a ratio to uranium (Ruhter 2011). Pantex analyzed air samples during work on the W55 program in June 1996 using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Scanning Electron Microscopy (SEM). Results were analyzed to determine a ratio of airborne thorium to depleted uranium in the workplace. All of samples had less than the detectable thorium concentration as measured by ICP-MS, although two had a single thorium particle observed by SEM. Thirty-nine percent of the samples had no detectable uranium and one sample had a detectable uranium signal that was less than the nominal detection level. Substituting half of the stated detection levels for the non-detected samples, the resulting mass ratio of thorium to uranium was 0.071 to 1. Assuming the uranium mass was from DU and the thorium mass was from ^{232}Th, the activity ratio, ^{232}Th to DU, was 0.018 to 1. Rounding to 2%, this ratio is proposed for assigning intakes of ^{232}Th relative to DU intakes for times when thorium was present during disassemblies. Equilibrium between ^{232}Th and its progeny will be assumed. This approach changes the temporal pattern of thorium intake from acute to chronic. Transcripts from the last WG meeting (*August 10, 2011*) appear to indicate that this method was acceptable. Much of the discussion centered on the ability to reconstruct DU; it was noted that if DU could not be reconstructed, thorium also could not be reconstructed.

3.2.5. Savannah River Site

A procedure (Butler 1969) was recently discovered that indicates that the actinide urinalysis method in use at SRS beginning in 1970 would have included thorium, in addition to americium, curium, and californium, in the extraction. There are results for urine samples analyzed with this method from several hundred workers each year. A coworker study will be developed, modeling these results as thorium and an intake rate assessed. This analysis is currently in process so has not yet been vetted through the Work Group.

3.2.6. Sylvania Corning-Bayside and Hicksville

The HSS website indicates that the Metallurgical Laboratory of the Sylvania Electric Company investigated uranium and thorium powder metallurgy. Thorium dust monitoring records exist, beginning in 1953, and from March, 1955, through June, 1957 (SRDB Ref ID 10358). Both breathing zone and general area sample data were available. There is no SEC period for this AWE site. The geometric mean of 43 breathing zone air samples is assigned to operations; the geometric mean of 44 general area samples is assigned to laborers and adjusted via Battelle-6000 (Battelle 2006) for supervisors and office workers. (*SCNC individual DR report*)

3.2.7. Texas City Chemicals

Texas City Chemicals produced uranium by recovery of U_3O_8 from a phosphate fertilizer production plant; thorium is present as a contaminant in the phosphate. This AWE has no personnel or workplace monitoring (SEC-00088). Surrogate data are used to assign uranium intakes; thorium is assigned based on the ratio determined for Blockson (NIOSH 2010a).

3.2.8. Westinghouse Nuclear Fuels Division

There is no SEC period for this AWE site. No thorium bioassay is available, but there are more than 6000 gross alpha air sample results for each year of operation (1971-1972). These results are largely from stationary air samples, collected on a daily or weekly basis, at strategic locations around the process areas and the stack, but also include some breathing zone (BZ) samples. A daily weighted average was established for 250 working days per year, from which inhalation and ingestion intakes at the 95th percentiles were determined. Intakes are assigned as uranium, plutonium, or natural thorium, based on which provides the most claimant favorable dose. (*WNFD individual DR report*)

3.2.9. Residual Periods

Many AWE sites have SEC classes established during their operations period because there were little-to-no bioassay and air monitoring data but for which a method was developed for the residual period. For all AWEs, the thorium intake assessments are based on gross alpha measurements of air concentration or surface contamination or by ratio to uranium. Methods applied for reconstruction during the residual periods include:

- **Norton**: The Norton Company processed both uranium oxide and thorium. There was no thorium bioassay and limited air concentration data during operations and clean up (SEC-00148, -00173). Residual period intakes are based on gross alpha air concentration levels from operations applied to the first year post cleanup and assigned as the most claimant favorable radionuclide (f*rom Norton individual DR report*).
- **Spencer Chemical Jayhawks Works**: Jayhawks Works processed unirradiated uranium scrap for the AEC, recovering enriched uranium from it for use in the weapons complex and was licensed to receive up to 10 kg of natural thorium oxide-uranium oxide mixture for use in process research. There was no thorium bioassay and limited air concentration data during operations and clean up (SEC-00089). Residual period intakes are based on gross alpha air concentration levels from operations applied to the first year post cleanup and assigned as the most claimant favorable radionuclide (f*rom Spencer Chemical Jayhawks Works individual DR report*).
- **BWXT**: A feasibility report from BWXT addresses a mixed uranium-thorium fuel (Jones 1959). There was no thorium bioassay and very limited air monitoring data during the operational period (SEC-00169, -00179). Intakes are derived from the administrative limit for surface contamination and then depletion factors were applied over time (*BWXT individual DR report*).
- **Metals & Controls**: The use of thorium at Metals and Controls is indicated in undated product literature and from a 1960 brochure. No thorium bioassay or air data are available during the operational period (SEC -00149). Residual period intakes are based on gross alpha surface contamination levels and assigned as the most claimant favorable radionuclide. These are applied with no source term depletion (*Metals & Controls individual DR report*).
- **Westinghouse Electric NJ**: The HSS website indicates that Westinghouse worked with thorium at the New Jersey location. No thorium bioassay or air data are available during the operational period. Residual period intakes are based on gross alpha surface contamination levels and assigned as the most claimant favorable radionuclide. These are applied with no source term depletion (*WEC-NJ individual DR reports*).

- **WR Grace Curtis Bay MD**: This facility processed monazite sand to extract thorium. No thorium bioassay or air data are available during the operational period (SEC-00182). The evaluation report (NIOSH 2011a) specifies that bounding residual period air concentrations can be based on measurements of air concentrations at similar facilities and knowledge of surface contamination levels within Building 23 at Curtis Bay during the post-operations period. Internal exposure during work in the Radioactive Waste Disposal Area can be bounded using soil concentration data collected during site remedial investigation activities along with an estimate of the particulate concentration in the air.
- **Ames:** Although not an AWE site, residual contamination following the cessation of thorium operations is discussed in the Ames site profile (ORAUT 2012). Thorium was refined between 1943 and 1953; this period is covered by SEC-00038, due primarily to a lack of thorium information. This was expanded in SECs-00075, -00166 and -00185 to include all employees through 1970, when renovation and demolition activities were complete.

  There were 160 urine samples analyzed for thorium in 1952-1953, with no routine thorium bioassay samples after this aside from urinalysis and nasal swipe results for four individuals involved in a thorium spill incident in 1957. Approximately 700 general and 270 breathing zone air samples for thorium were collected in an AEC study performed in March 1952, as well as some air sampling data from Wilhelm Hall in February 1953.

  Residual contamination was still a possibility after thorium operations ceased. Intakes are assigned from a single exponential decay of available activity over time in a facility, spanning from 1955 to 1995. Survey results from a 1952 assessment were used as an upper bound for 1955 because there was no information from 1955. The upper bound for 1995 was based on removable surface contamination and resuspension from a survey of the pipe tunnel.

- **Lake Ontario Ordnance Works:** Thorium has been identified as being present on site but of unknown quantity. It was used for interim storage of uranium and thorium billets and rods processed by other New York companies in the 1950s. As with Ames, LOOW is a DOE site that has a residual contamination following the cessation of shipments. LOOW is covered by an SEC (00145) through 1953, at which time radioactive material shipments to the site ceased. There are no thorium bioassay results but there is some bioassay for uranium and radium. Occupational thorium intakes are based on ratios to radium and uranium. For unmonitored individuals, there is a potential for intakes of radioactive materials from uncovered storage piles and any other potential activities while the site was in caretaker status. For these individuals, intakes are assigned based on soil analysis results, with a mean activity established. A daily weighted average is then determined based on standard breathing rates, 250 working days per year, and an assumed air suspension rate at the OSHA regulatory limit of 15 mg/m^3. (*LOOW individual DR report*)

3.3. Feasible Thorium Dose Reconstruction

Methods here include those where an SEC that included thorium was specifically denied or where a class was established for nuclides other than thorium.

3.3.1. Blockson

The Blockson Chemical Company facility separated uranium from phosphoric acid. The phosphate rock source contains trace amounts of natural thorium. One hundred twenty two uranium urine samples were collected from 25 employees between 1954 and 1958. These are the only radiological results from the AEC operational period (1954-1960). The operations period has an SEC (SEC-00058) class due to radon. Th-232 is considered to be present at a bounding ratio of 30 to 1, U-238 to Th-232 (NIOSH 2010c).

3.3.2. Fernald

Daily weighted average exposure air monitoring data are proposed to bound worker exposures to thorium for the period from 1953 to 1967 (Morris 2010). Available DWE data represent six plants (1, 2/3, 4, 6, 8, 9), 14 different years, 142 different job descriptions, 361 different operations, and 16,748 air samples. Air sampling duration ranged from one minute to 455 minutes, with the average being 63 minutes. All SC&A findings related to this method were resolved during the Fernald Work Group meetings and remaining issues were found to be site-profile rather than SEC related (April 19, 2011 transcript).

3.3.3. Mound

Potential unmonitored exposure to radium-actinium-thorium from K-65 sludge form the basis of SEC-00090 (NIOSH 2007), covering the period from 1949 to 1959. Thorium was not the primary nuclide in the mix; Ac-227 was of interest and was the focus of the recovery program. Later thorium work centered on Th-232. A routine thorium urinalysis program was in place during these thorium operations at the site, which NIOSH proposed to use for individual dose assessments. There is no proposed method for unmonitored workers. The Work Group had no issues with the assessment methods; the concern was data adequacy and whether everyone who was potentially exposed was monitored. The issue was closed after some discussion (*Mound WG June 5, 2012 transcript*), although there was no clear resolution. The general consensus seemed to be that monitoring was adequate, although much of it falls into an SEC period.

3.3.4. United Nuclear Corporation (UNC)

A single thorium-specific project was conducted in the Pellet Plant in 1964. No thorium bioassay was collected. A total of 210 air samples, designated specifically as "Th02" (thorium dioxide), were collected throughout the project (NIOSH 2011b). Data from the 210 air samples were used to determine the parameters of a lognormal distribution. Operators who routinely handled thorium or operated thorium-processing equipment are assigned the 95th percentile of this distribution as a constant. Supervisors, laborers, and other personnel who routinely entered the processing area but did not routinely handle thorium are assigned the full distribution. Personnel who did not routinely enter the area are assigned the geometric mean of the distribution. The UNC SEC petition (SEC-00116) was denied, so this method is accepted as a valid bounding dose reconstruction approach for thorium at UNC.

3.3.5. Weldon Spring

Two petitions (SEC -00143 and -00144), covering 1957 through 1966, were received and evaluated, with no resulting SEC periods.

There are no quantitative bioassay results for thorium, although there are 200 qualitative chest count results from July 1966. The Y-12 MIVRML was used for these measurements. Air sampling was the primary method for monitoring and controlling intakes. Both breathing zone and general area air samples were collected and the samples were analyzed by direct alpha count with laboratory scintillation counters. A DWE concentration index was calculated based on a combination of these samples.

The assessment method originally proposed in the site profile (ORAUT 2005b), based on the assumption of exposure to multiples of the maximum airborne concentration limit for various amounts of time, was not accepted. The SEC evaluation report (NIOSH 2010d) developed and proposed a revised methodology based on the air monitoring records. Thorium intake rates will be based on DWE air sample concentration measurements of thorium dust taken during thorium processing operations. The measured alpha air concentration will be assumed to be associated only with ^{232}Th and ^{228}Th, which are the isotopes found in thorium processed at the Weldon Spring Plant site. Measured alpha activity will be partitioned in a 1-to-1 ratio of ^{232}Th to ^{228}Th. In addition, ^{228}Ra, which is a beta emitter that would not have been detected in the gross alpha count, will be added in a 1-to-2 ratio of ^{232}Th to ^{228}Ra. For inhalation, the intake rate will be based on the product of DWE, breathing rate and number of working hours per year. Uncertainty in the DWE will be computed in accordance with Battelle-TIB-5000 (Battelle 2007), which provides an approach for estimating overall uncertainty when only summaries of the time-weighted average data are available. The uncertainty is evaluated by fitting lognormal distributions to the data for each job title and performing a Monte Carlo simulation. Additional parameters from this document will be incorporated in the simulation to account for the lack of representativeness of air samples. When the actual location of a worker is not known, the maximum measured DWE for that period of time and full-time occupancy during the work day will be assumed.

This methodology was last discussed at the February 2012 Weldon Spring Work Group meeting (*February 14, 2012 transcript*). During this meeting there was a petitioner-raised issue regarding the presence of thorium outside of the period addressed by the proposed methodology. Further research (Harrison 2012) indicated that this was ^{230}Th rather than ^{232}Th. During the September 2012 Advisory Board meeting (*September 19, 2012 transcript*), the motion that "we accept the agency's position that they can, in fact, complete adequately the dose reconstructions that are necessary for the claimants at Weldon Spring" was passed and the proposed methodologies therefore accepted.

4. Summary

Thorium dose reconstruction appears to be feasible at a number of sites for at least some time frames. The majority of sites with an accepted or unreviewed method are AWEs or small DOE facilities that performed work similar to that at the AWEs. Several of these sites produced uranium from phosphate so thorium is of secondary concern to uranium and can frequently be tied directly to the uranium values by a ratio. Where gross alpha measurements were taken and thorium and uranium work performed in the same areas, the gross alpha measurement can be interpreted as either uranium or thorium and the more favorable-to-claimant assessment made. Many of the AWEs have an SEC during their operational periods, most frequently due to a lack of monitoring data, but accepted dose reconstruction methods for their residual periods. In such cases, no new source term is being generated so limited data can be used to make assumptions over extended periods of time.

For the larger DOE facilities, there were two primary methods applied.

1) In the case of Mound, there was a routine thorium bioassay program in place during the primary thorium use activities. To date, this appears to be unique to Mound. Thorium use at the site was limited to specific projects and areas, and there is documentation of the workers involved in these activities. As noted in the discussion on Mound in Section 3.3.3, the majority of the thorium work was performed during the SEC period, so there was not a large push to develop methodologies for assigning intakes to workers who might have had a potential for more casual contact with the material. However, the use of the existing data was found to be adequate for those working directly on the thorium processes.
2) Fernald and Weldon Spring had extensive workplace air monitoring for thorium operations and used these results to calculate daily weighted average exposures. Results of individual samples were not available for either site, but the number of samples that went into the DWE calculation, as well as the high, low and average air sample results, and in the case of Fernald, the length of time over which the samples were collected, were found in site documentation. Number of workers in an area and categories that indicated the job function were also included with the DWE information. These data could be used to determine the distribution of the data. United Nuclear Corporation also conducted air monitoring throughout the single thorium project at the site. Results from the individual samples were available and found to be adequate for assessing potential thorium intakes.

A third possibility is the use of chest count measurements for Pb-212 and Ac-228. This methodology is still in discussion for application at Fernald.

5. Conclusions

This review of thorium internal dose reconstruction methodologies indicates that it is possible, with caveats discussed below, to bound doses from intakes of thorium if we have one or more of the following:

1) Representative thorium air monitoring results.

2) Routine thorium urinalysis program.
3) Ac-228 and Pb-212 *in vivo* results along with a way of characterizing the thorium mixture that might have been inhaled.
4) Gross alpha air concentrations or resuspension factors applied to surface contamination levels to estimate air concentrations during the residual periods.

In general, it appears that thorium is seen as a primary nuclide at many sites where it is present rather than as an "exotic" nuclide, a term generally reserved for those radionuclides used only in special or short-term activities, and for which less rigorous methodologies are sometimes found to be acceptable. As such, the quantity of data and level of effort needed for reconstruction is similar to that needed to assess primary nuclides such as uranium or plutonium. In most cases this means that it is expected that bioassay monitoring was conducted when there was a potential for exposure, covering at a minimum those with the highest potential for intakes. If this is not available, then representative, preferably breathing zone, air monitoring can be used as long as it can be demonstrated that it was indeed representative, and that there are data from all major locations where thorium was in use. Data also need to cover a large portion of the time during which thorium is a concern at a facility.

6. References

Battelle, 2006, *Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium*, Battelle-TBD-6000, Rev. F0, Battelle Team Dose Reconstruction Project for NIOSH, SRDB Ref. ID 30671.

Battelle, 2007, *Default Assumptions and Methods for Atomic Weapons Employer Dose Reconstructions*, Battelle-TIB-5000, Rev. 00, Battelle Team Dose Reconstruction Project for NIOSH.

Butler, F.E. and R.M. Hall, 1969, *Determination of the Actinides in Biological Samples with a Bidentate Organophosphorus Extractant* (DP-MS-69-73), Savannah River Laboratory, Aiken, South Carolina, SRDB Ref. ID: 49190

Harrison, D., R.L. Morris, D. Stempfley, and M. Harrison-Maples, 2012, *White Paper, Examination of the Weldon Spring Site Profile Approach to Thorium-230*, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee.

Jones, C.H., 1959, *Feasibility Report No. 10*, Babcock & Wilcox Company, Lynchburg, Virginia, SRDB Ref. ID: 74811.

Morris, R.L., 2010, *White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate*, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee.

NIOSH (National Institute for Occupational Safety and Health), 2006, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00046*, *Fernald*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2007, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00090*, *Mound Plant*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2008, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00057-2*, *Hanford*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2009a, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00109 Rev. 0*, *Los Alamos National Laboratory*, Office of Compensation Analysis and Support, Cincinnati, Ohio, SRDB Ref. ID 79895.

NIOSH (National Institute for Occupational Safety and Health), 2009b, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00149*, *Metals and Controls Corporation*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2010a, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00088*, *Texas City Chemicals,* Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2010b, *Special Exposure Cohort Petition Evaluation Report Addendum, Petition SEC-00103, Savannah River Site*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2010c, *Technical Basis Document for Atomic Energy Operations at Blockson Chemical Company, Joliet*, *Illinois*, DCAS-TKBS-0002, Division of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2010d, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00143, Weldon Spring Plant*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2011a, *Special Exposure Cohort Petition Evaluation Report, Petition SEC-00182*, *W.R. Grace and Company (Maryland)*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2011b, *Technical Basis Document for the United Nuclear Corporation Hematite, Missouri*, DCAS-TKBS-0008, Division of Compensation Analysis and Support, Cincinnati, Ohio.

NIOSH (National Institute for Occupational Safety and Health), 2012, *Special Exposure Cohort Petition Evaluation Report Petition SEC-00201*, *Hanford*, Office of Compensation Analysis and Support, Cincinnati, Ohio.

ORAUT (Oak Ridge Associated Universities Team), 2003, *Technical Basis Document for the Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site, St. Louis, Missouri, Period of Operation 1942-1958*, ORAUT-TKBS-0005, Rev. 00, Oak Ridge, Tennessee. SRDB Ref. ID 19783.

ORAUT (Oak Ridge Associated Universities Team), 2005, *Savannah River Site*, ORAUT-TKBS-0003-5, Rev. 03, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2005, *Weldon Spring Plant – Occupational Internal Dose*, ORAUT-TKBS-0028-5, Rev. 00, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2007, *Internal Dosimetry Coworker Data for the Hanford Site*, ORAUT-OTIB-0039, Rev. 01, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2009, *Los Alamos National Laboratory – Occupational Internal Dose*, ORAUT-TKBS-0010-5, Rev. 01, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2010a, *Analysis of Savannah River Site Thoria and Thoron Air Sampling Data as a Method of Intake Bounding between 1965 and 1971*, ORAUT-RPRT-0046 Rev. 00, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2010b, *Hanford Site – Site Description,* ORAUT-TKBS-0006-2, Rev. 02, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2010c, *Technical Basis Document for the Hanford Site – Occupational Internal Dose*, ORAUT-TKBS-0006-5, Rev. 03, Oak Ridge, Tennessee.

ORAUT (Oak Ridge Associated Universities Team), 2012, *Site Profile for Ames Laboratory*, ORAUT-TKBS-00055, Rev. 03, Oak Ridge, Tennessee.

Poppleton, H.O., 1979, *Albany Research Center Site History*, Albany, Oregon, SRDB Ref. ID 120443

Ruhter, P.E. and B.P. Smith, 2011, *White Paper, Pantex Bounding Uranium and Thorium Intakes*, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee.