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SC&A REVIEW OF ADDENDUM 3 TO THE NIOSH SAVANNAH RIVER SITE SPECIAL EXPOSURE COHORT (SEC-00103) EVALUATION REPORT

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Prepared by

Joyce Lipsztein
Arjun Makhijani
Harry Chmelynski
Bob Barton

S. Cohen & Associates
1608 Spring Hill Road, Suite 400
Vienna, Virginia 22182

Saliant, Inc.
5579 Catholic Church Road
Jefferson, Maryland 21755

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Task Manager: _____ Date: Arjun Makhijani, PhD	Supersedes: N/A
Project Manager: _____ Date: John Stiver, MS, CHP	Reviewers: Kathy Behling Joe Fitzgerald, PhD

Record of Revisions

Revision Number	Effective Date	Description of Revision
0 (Draft)	09/04/2013	Initial issue
1 (Draft)	09/12/2013	Reference information has been clarified. Typographical errors have been addressed. Technical clarification added. Two attachments (Attachments C and F of Rev. 0) have been removed from this revised document and are now included in the reference list.

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ABBREVIATIONS AND ACRONYMS

Advisory Board or ABRWH	Advisory Board on Radiation and Worker Health
Am	americium
AMAD	Activity Median Aerodynamic Diameter
BOMAB	Bottle Manikin Absorption
Bq	Becquerel
CDC	Centers for Disease Control and Prevention
Ce	cesium
Cf	californium
cm	centimeter
Cm	curium
CTW	construction trades worker
d/m/L	disintegrations per minute per liter
dpm	disintegrations per minute
DOE	(U.S.) Department of Energy
DTPA	diethylenetriamine pentaacetic acid
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ER	Evaluation Report
GM	geometric mean
GSD	geometric standard deviation
HHF	H modified high heat feed
HMF	H modified medium heat feed
HM process	Heavy Metal process
HP	Health Physicist
HPT	Health Physics Technology
IMBA	Integrated Modules for Bioassay Analysis
keV	kilo-electron volt
kg	kilogram
L	liter
LANL	Los Alamos National Laboratory
LN	lognormal

LOD or LD	limit of detection
LWR	light water reactor
µm	micrometer
mCi	millicuries
MDA	minimum detectable activity
MPM	maximum possible mean
Mrem	millirem
mSv	millisievert
NaI	sodium iodide
nCi	nanocurie
NCW	non-construction trades worker
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH/OCAS Claims Tracking System
Np	neptunium
OPOS	one person-one sample
ORAUT	Oak Ridge Associated Universities Team
ORNL	Oak Ridge National Laboratory
Pa	lead
PAS	personal air sampler
Pb	protactinium
pCi	picocurie
Pu	plutonium
Ra	radium
RBOF	Receiving Basin for Offsite Fuel
RCO	Radiological Control Operations
Rn	radon
ROI	region of interest
ROS	regression on order statistics
SC&A	S. Cohen and Associates (SC&A, Inc.)
SEC	Special Exposure Cohort
Sr	strontium
SRDB	Site Research Database
SRS	Savannah River Site

TBD	technical basis document
Th	thorium
TIOA	tri-isooctylamine
U	uranium
WBC	whole-body count(ing)
WRS	Wilcoxian Rank Sum Test

EXECUTIVE SUMMARY

This report reviews the National Institute for Occupational Safety and Health's (NIOSH's) proposed methods for estimating thorium-232 intakes by workers at the Savannah River Site (SRS). It covers the period October 1, 1972, to December 31, 2007, which is the period still under review for SEC-00103. This Special Exposure Cohort (SEC) petition relates to the feasibility of dose reconstruction with sufficient accuracy for construction trades workers (CTWs) at SRS. In December 2011, the Advisory Board on Radiation and Worker Health (Advisory Board or ABRWH) recommended that SRS employees who worked up to September 30, 1972, and met other necessary criteria, be added to the SEC (ABRWH 2011).

A number of issues relevant to the SEC remained for the October 1, 1972, to December 31, 2007, period. They were summarized in an issues matrix prepared by SC&A in 2011 (SC&A 2011). One of these issues was dose reconstruction for CTWs who had the potential for exposure to Th-232. Another issue was the construction of a coworker model that would estimate doses for CTWs who do not have relevant monitoring data.

NIOSH published a document describing coworker models for various radionuclides, including Np-237, in 2013 (ORAUT 2013). It also published Addendum 3 to its SRS SEC Evaluation Report (ER), in which the approach to thorium dose reconstruction as well as source term data are described (NIOSH 2012). A part of the NIOSH approach would be to use bioassay data for the trivalent actinides, Am, Cm, and Cf, for constructing a coworker model to estimate doses for any of those three radionuclides or for thorium. NIOSH published a report comparing distributions of trivalent actinide data for non-construction worker (NCW) data to CTW data to check whether the distributions can be considered the same. NIOSH published a report on this topic in 2012 (ORAUT 2012a). Since NIOSH proposes to use data for all workers to prepare the coworker model based on its conclusion that the distributions of the measurements of CTW and NCWs were the same, it was necessary to review the data for all workers, even though SEC-00103 is for CTWs. This coworker model would be used for CTWs and NCWs, as well as workers that are presently not definitively classifiable in either category. Finally, NIOSH published a general approach to comparing measurements for two groups of workers to determine if they were drawn from the same distribution in 2012. This document proposes to average raw worker data to yield a "one person-one sample" (OPOS) result. The comparisons of the distributions of the two groups of workers are made using OPOS results derived from the raw data. The period of averaging of raw data is usually, but not always, 1 year (ORAUT 2012b).

This SC&A report reviews the four NIOSH reports mentioned in the prior paragraph, as well as other documents as they may relate to the technical soundness of NIOSH's proposals for thorium dose estimation. In the course of this review of thorium, certain issues that were relevant to the three trivalent radionuclides (Am, Cm, and Cf), as well as to other radionuclides for which NIOSH has proposed the same approach (mixed fission products, neptunium-237), came to light. These are also discussed. However, it should be borne in mind that this report is not a complete review of the NIOSH approach for these radionuclides; rather, only some common issues are highlighted here. SC&A further notes that some issues, such as monitoring practices in relation to workplaces where thorium was handled and processed, require worker interviews and some further onsite document review. This has been a long and complex process, in part due to

budgetary issues, and is an ongoing activity. This report may be revised should worker interviews as well as onsite review of documents not yet available bring new issues to light or throw new light on issues related to dose reconstruction raised here. However, the essential findings on the dose reconstruction methods proposed by NIOSH, including the coworker model, do not depend on those interviews and can be reviewed independently of them.

One major question in the review was whether thorium would be extracted along with trivalent actinides in the SRS bioassay sample analysis procedure used in the 1972–1989 period. If that were not the case, trivalent actinide data could not be used for thorium dose estimation even if there were no other issues with the proposed method. SC&A reviewed this issue and agrees with NIOSH's conclusion that the thorium extracted along with Am/Cm/Cf in the SRS laboratory bioassay procedure is scientifically reasonable and well-supported.

The 32 findings below summarize the main conclusions of SC&A's review. Since NIOSH's models include the use of NCW data for constructing coworker models and dose reconstruction models for CTWs, the SRS Work Group had previously asked SC&A to comment on NCW issues if they came up in the course of CTW issues (ABRWH 2010, pp. 70–77). The applicability of SC&A's findings is as follows:

- Findings 1 to 4, Findings 13 to 20, Finding 22, and Findings 25 to 32 are generally applicable to all workers.
- Findings 5 to 12, Finding 21, and Finding 23 apply to CTWs.
- All findings, except Findings 1 though 4, are also applicable to Am, Cm, Cf dose reconstruction.

SC&A also has an overall finding on the OPOS approach that NIOSH is proposing to use for its coworker model for thorium and for the trivalent actinides Am, Cm, and Cf.

Overall Finding on the One Person-One Sample Database and Model for Thorium and the Trivalent Actinides: The OPOS approach that NIOSH has adopted for trivalent actinides and thorium contains many fundamental problems, including large numbers of negative OPOS values in several years. In addition, many of the raw data records also appear to be unreliable, since widely different measurement results were obtained from different discs prepared from the same bioassay sample. As they stand, the problems with the data, the coworker model, and the OPOS results are severe enough to make their use for dose reconstruction scientifically unacceptable.

Finding 1: NIOSH has characterized various thorium storage and processing activities in its latest Addendum to the Evaluation Report (NIOSH 2012). However, NIOSH's catalog of places and times where such activities were carried out is not complete. A more complete description of the source term is needed for scientifically reasonable thorium dose reconstruction by the methods proposed by NIOSH.

Finding 2: Significant amounts of thorium were involved in some activities, such as using thorium as a surrogate for plutonium-238. NIOSH's argument that the amounts of thorium involved were far smaller than those of other radionuclides is not relevant to the feasibility of

thorium dose reconstruction. Thorium-232 exposures need to be considered in their own right at SRS during the 1972–2007 period as they have been at other sites and at SRS during the period prior to October 1, 1972.

Finding 3: NIOSH's Addendum 3 to the Evaluation Report has not investigated thorium-related incidents beyond mention of the Special Hazards Investigations database, which is known to be incomplete. That database was not designed to be a comprehensive record of incidents. A more detailed investigation of thorium-related incidents appears to be warranted, especially since some of the bioassay data that NIOSH proposes to use is related to trivalent actinide incidents.

Finding 4: NIOSH has not discussed the radon-220 source term derived from the storage of thorium-232. The radon-220 dose could be important in some circumstances where there was significant residual thorium or where thorium was stored in significant amounts. This includes at least two high-level waste tanks.

Finding 5: SC&A has concluded that NIOSH's method for comparing the measurements of two sets of workers requires that the monitoring protocols of the two sets of workers were the same. NIOSH has stated that the protocol for CTW bioassays was different. As a result, the method used by NIOSH to compare CTW and NCW Am/Cm/Cf data does not meet the requirements for a valid comparison of the two bioassay datasets for the 1972–1989 period.

Finding 6: NIOSH's coworker model for thorium is based on its conclusion that CTW and NCW bioassay samples are drawn from the same distribution. A corollary of Finding 5 above is that NIOSH's coworker model, which combines NCW and CTW data, is based on an invalid comparison and therefore is not suitable for estimating CTW thorium doses for the 1972–1989 period.

Finding 7: The SRS emphasis on incident-related monitoring of CTWs at SRS does not necessarily reflect differences between CTW work and NCW work. As a result, the emphasis on incident-related monitoring may have missed routine exposures for at least some CTW job types.

Finding 8: The number of CTW data points is less than 30 in each aggregated period during 1984–1989. This is less than the minimum number required for a valid comparison between CTWs and NCWs. Therefore, NIOSH's conclusion that CTW and NCW sample distributions are the same is not valid for this period. As a result, the coworker model based on this conclusion has not been shown to be valid for this period.

Finding 9: While NIOSH has not provided disaggregated data for 1981 and 1982, the number of CTW data points for 1982 is less than 30. Hence, the data for 1982 are also insufficient for a CTW-NCW distribution comparison.

Finding 10: Aggregating data over more than 1 year without reference to underlying processes and other data is not justifiable. NIOSH should provide a technical rationale for treating 1981–1982 and 1987–1989 differently than other years. Aggregation over more than 1 year to increase the number of data points is not a suitable technical rationale. If no sound basis can be provided for aggregating data over more than 1 year, NIOSH should do annual aggregating for calculating OPOS values. This is important for evaluating NIOSH's conclusion that CTW and NCW data

are drawn from the same distribution. Furthermore, aggregation over multiple years rather than a single year to estimate an OPOS value increases the risk that the result would represent a mix of thorium exposure and Am/Cm/Cf exposure, rendering it scientifically questionable.

Finding 11: NIOSH has not demonstrated that the number of CTW samples is sufficient to simultaneously maintain low levels of Type 1 and Type 2 errors (for instance, less than 5% for Type 1 errors and less than 15% for Type 2 errors), even in the years when CTWs have more than 30 samples. SC&A's analysis indicates that when the geometric standard deviation (GSD) is much larger than the ratio of CTW to NCW geometric means (GMs), the rate of Type 2 errors will tend to be high. Type 2 errors occur when the null hypothesis (distributions are the same) is incorrectly accepted.

Finding 12: In some years, the number of data points is inadequate to make a valid comparison between CTWs and NCWs in regard to trivalent actinide data distributions, even when there are more than 30 data points. In other cases, there are sufficient data. NIOSH has not analyzed the problem of data adequacy as a function of relative GM and GSD values. Such an analysis is essential for evaluating data adequacy for comparing CTW and NCW distributions.

Finding 13: NIOSH's interpretation of below minimum detectable activity (MDA) results for OPOS calculations is an interpretation of data entry conventions that contains an element of arbitrariness. It is systematically claimant unfavorable when a large fraction of the results are well below the MDA. This finding applies to all cases where NIOSH proposes to use OPOS data as presently calculated for coworker models, including those whose data are reviewed in this report (Am, Cm, Cf and thorium) as well as others, such as neptunium and fission products.

Finding 14: NIOSH's approach to using data well below the MDA, including negative numbers and zeros to calculate OPOS values, can sometimes yield scientifically meaningless results such as negative OPOS values, implying negative intakes. The problem of negative OPOS results is especially prevalent in the 1983–1989 period.

Finding 15: The present NIOSH method of calculating OPOS data would result in systematically very claimant-unfavorable results in the case of the Am, Cm, Cf dataset. This would be true of thorium dose estimates as well as Am, Cm, Cf dose estimates. This is because the vast majority of bioassay results for the 1972–1989 period are well below the MDA.

Finding 16: SC&A is concerned that some reported results in the logbooks that are above the MDA are averages of results that are both well below and well above the MDA. This is much better than the NIOSH OPOS procedure when even below MDA results are used at face value, but it is still a concern since such practices vitiate the connection between the raw data and the workers' intake experience in the real world.

Finding 17: NIOSH's coworker data compilation procedure states that chelation-related bioassay samples were excluded from OPOS calculations. However, SC&A found that, contrary to this procedure, chelation-related samples were included in the OPOS averages in every case.

Finding 18: SC&A's examination of the raw data with reported results above the detection limit shows that sometimes the same urine sample, counted in different discs, presents inconsistent results. This indicates that the method used for detection of activity was not always reliable; such widely inconsistent results from the same urine sample cannot be trusted.

Finding 19: Many reported OPOS values that are above the detection limit are actually the average of negative and positive normalized disc results, or are the average of results with large differences among the different discs derived from the same urine sample. Such average results no longer retain an unambiguous connection to the intake of the worker, do not represent excretion rates of workers, and therefore should not be used to calculate intake rates.

Finding 20: Many reported OPOS results below the detection limit are the average of normalized disc results that have a large variation between them. This indicates that the resultant average of disc results is highly uncertain. Such average results do not have an unambiguous connection to the intake of workers, do not represent excretion rates, and should not be used to calculate intake rates.

Finding 21: The number of data points for CTW job types is inadequate to compare relative thorium exposure potential for CTW job types for the 1972–1989 period or to compare the exposure potential of specific CTW job types with NCWs.

Finding 22: Trivalent actinide OPOS results can only be applied in a scientifically defensible way if there is knowledge of whether the worker was exposed to one of the trivalent radionuclides or to thorium. Intake results would not be scientifically credible in the absence of this information.

Finding 23: NIOSH has not provided evidence that there are data to differentiate between thorium and trivalent actinide exposure. In the absence of such information, it is not possible to establish whether the bioassay data for NCWs and CTWs represent comparable intake conditions.

Finding 24: Lung doses for trivalent radionuclides, which NIOSH always interprets as Type M, would be far lower than the lung dose when the same bioassay data are interpreted as Type S thorium. Scientifically reasonable dose estimates therefore require knowledge of the time and place of exposure potential to thorium for workers with Am/Cm/Cf bioassay data. NIOSH has not shown that it has the necessary information to interpret the bioassay results as thorium instead of the specific trivalent radionuclide(s) noted in the bioassay record.

Finding 25: Incorrectly assigning a trivalent radionuclide dose conversion factor to a worker exposed to Type S thorium would yield a very claimant-unfavorable lung and bone dose estimate.

Finding 26: Incorrectly assigning a Type S thorium lung dose to a worker exposed to Type M Am, Cm, or Cf would result in a very large and scientifically unwarranted overestimate of the dose. Assigning all intakes to thorium when the exposure was actually to a mixture of the various radionuclides would also overestimate the lung and bone dose.

Finding 27: The MDAs for thorium by chest counting in the 1990 Internal Dosimetry document are far higher than the 100 millirem level required to initiate routine monitoring.

Finding 28: Due to conflicts between statements in the NIOSH ER and in the SRS Internal Dosimetry 2001 technical basis document (TBD), it is not possible for SC&A to definitively establish the date when the MDAs for chest counting described in Internal Dosimetry 2001 became operational. This problem would apply specifically to the 1990–1994 period.

Finding 29: NIOSH has not compiled in-vivo counting data for the 1990–2007 period (including detection limits) that would be relevant to thorium intakes. Therefore, it is not possible for SC&A to evaluate whether thorium exposure potential was low or whether at least some fraction of workers, possibly small, had significant thorium exposure potential. It is also not possible to evaluate whether the quantity and quality of data are adequate for thorium dose estimation in the 1990–2007 period.

Finding 30: The FASTSCAN specifications indicate that the detection limit for thorium would be so high as to render it practically undetectable in SRS workplace situations.

Finding 31: NIOSH has not provided information on how it will distinguish between Pb-212 results due to thoron from those resulting for thorium-232 intakes.

Finding 32: In the absence of a compilation of whole-body count (WBC) and chest count data, it is difficult to see how NIOSH will assign thorium doses to workers or construct a coworker model for the 1990–2007 period. There were thorium-related activities at SRS during this period.

1.0 INTRODUCTION

A number of issues that might impact NIOSH's ability to reconstruct doses of Savannah River Site (SRS) Construction Trade Workers (CTWs) were identified in an issues matrix that was updated in December 2011 (SC&A 2011), after the Advisory Board on Radiation and Worker Health (ABRWH) voted to recommend the addition of qualified SRS employees in the period January 1, 1954, to September 30, 1972, to the Special Exposure Cohort (SEC). The relevant SEC petition is SEC-00103. Many of the issues were rendered moot for SEC review purposes by the ABRWH decision, since they were entirely covered by the period for which the ABRWH recommended an SEC. However, a number of issues that were relevant beyond September 30, 1972, up to the end of 2007 period remained. SC&A identified them in a revision of the SEC issues matrix in December 2011 (SC&A 2011). For several of the remaining issues, NIOSH was to propose methods for dose reconstruction in these cases, including coworker models, to demonstrate the feasibility of dose reconstruction with sufficient accuracy for specific radionuclides or groups of radionuclides.

This report reviews NIOSH's proposed method for estimating CTW exposures to thorium-232 for the period October 1, 1972, to December 31, 2007. Please note that for brevity, we use "1972" to refer to the period "October 1, 1972, to December 21, 1972," in this report. NIOSH proposed its thorium dose reconstruction method in Addendum 3 of its Evaluation Report (ER) for SEC-00103 (NIOSH 2012). SC&A sent some questions about thorium (and neptunium) dose reconstruction methods proposed by NIOSH; they were discussed during a technical call in January 2013. The notes of that call are reproduced in Attachment A; NIOSH's written responses are reproduced in Attachment B. The questions are also reproduced in each of these attachments.

NIOSH has proposed two quite different dose reconstruction methods for thorium for different periods. In Addendum 3 of its ER, NIOSH proposed to use americium/curium/californium (Am/Cm/Cf) trivalent actinide urine data to estimate thorium doses for the 1972–1994 period (inclusive) and WBCs data for the 1995–2007 period inclusive (NIOSH 2012, pp. 28–30). However, during a technical call in January 2013, NIOSH revised the periods and stated that it would use the urine data up to 1989 and the WBC data from 1990 onwards (see Attachment B).

Since NIOSH proposes to use Am/Cm/Cf bioassay data for thorium dose estimation in the 1972–1989 period, it was necessary to review that data and the CTW-non-construction worker (NCW) comparisons made by NIOSH to build the Am/Cm/Cf coworker model. Some of the findings of this SC&A review, therefore, also apply to the three trivalent actinides, Am, Cm, and Cf. These are specifically called out in the Executive Summary, but not in the body of the report.

This review consists of four parts:

(1) A review of NIOSH's presentation of the thorium source term (Section 2)

(2) A review of the use of one person-one sample (OPOS) approach in general for aggregating data for the purpose of comparing distributions of measurements of two groups of workers (Section 3)

(3) A review of the adequacy of trivalent actinide data at SRS for comparing CTWs and NCWs and of the methods used by NIOSH to compile SRS OPOS data (Section 4)

(4) A review of the application of trivalent actinide bioassay data to thorium dose reconstruction for the 1972–1989 period (Section 5)

(5) A review of NIOSH's proposal to use WBC data for estimating thorium intakes for the 1990–2007 period (Section 6)

2.0 THORIUM SOURCE TERM

Addendum 3 to the SRS ER for SEC-00103 addresses NIOSH's approach to thorium dose reconstruction at SRS primarily to assess the "feasibility of bounding doses from thorium exposures received during the expanded time period from October 1, 1972 through December 31, 2007" (NIOSH 2012, p. 4). NIOSH 2012 describes the processing, research, and storage of thorium at SRS. Table 5-2 presents the quantities of thorium located throughout the facility during the SEC period. The majority of the thorium onsite was in storage in the Receiving Basin for Offsite Fuel (RBOF); however, most of the research and activities involving thorium occurred in Buildings 773A and 235F. NIOSH also found that thorium activities and storage occurred in Buildings 723A, 772F, M Area, 777M, 217-A, 100K Basin, and 100L Basin. Table 5-3 of the Addendum presents an annual timeline of thorium-related activities and their locations along with the associated inventories. In support of the SEC review, SC&A conducted research using the Site Research Database (SRDB) in order to assess the information provided by NIOSH in Tables 5-2 and 5-3 of the Addendum.

SC&A's query of SRS documents with the keyword "thorium" resulted in over 800 documents, most of which are dated prior to 1972. Approximately 130 documents contained information relevant to our review, which included, but were not limited to, SRS publications, laboratory reports and notebooks, memos, correspondence, radiation survey reports, internal dosimetry records, and worker interviews. Although SC&A did not perform a comprehensive search of the thorium activities at SRS, we did attempt to collect as many time period and location details as possible from the SRDB documents.

Table 1 shows the results of SC&A's review. It reproduces the part of Table 5-3 in Addendum 3 of the ER (NIOSH 2012) that shows where thorium was stored or handled in various years and the quantities involved. NIOSH has also described a number of activities that involved thorium handling or processing (NIOSH 2012, pp. 7–14). SC&A also compared its review with the storage locations listed in Table 5-2 of NIOSH 2012.

SC&A's thorium query of the SRDB also yielded numerous files of individual workers. A review of the internal dose records of 28 workers indicated that the files did not contain information on areas of thorium work in the 1972–2007 period not identified by NIOSH in Table 5-3.

SC&A verified NIOSH's conclusions regarding the areas where thorium was stored and the kinds of activities that were conducted using thorium during the 1972–2007 period. SC&A also reviewed some examples of thorium activities to examine the quantities of thorium that were processed in various activities. Table 1 summarizes the results of SC&A's review.

SC&A's review found that NIOSH has described the types of activities that occurred with thorium in the period in question in Section 5 of Addendum 3 of the ER (NIOSH 2012, pp. 6–17). However, the year-by-year catalog of storage locations and activities shown in Table 5-2 and Table 5-3, and the descriptions in the text do not fully reflect the activities that were carried out. For instance, removal of thorium from plutonium scrap is mentioned only for 1977 (NIOSH 2012, p. 9). But the limited survey done for this review indicates that thorium recovery from

plutonium scrap occurred at other times. As an example, tests were done in the HB-line in 1995 to remove thorium from plutonium-238 scrap; some of the scrap contained as much as 10% thorium. The description makes it clear that the process was to be used as a routine activity to produce Pu-238 for Los Alamos (WSRC 1995, pp. 17–18). SC&A has not attempted to track the amounts and times of thorium recovery from plutonium scrap or the full extent of the process development activities. NIOSH should provide full documentation of the times and places of thorium activities; this is essential for a scientifically reasonable interpretation of the data that NIOSH proposes to use (see Section 5 of this report).

As another example, Table 5-3 in NIOSH 2012 has many entries for the use of thorium as a surrogate radionuclide. The references provided by NIOSH (Peeler and Edwards 2003 and Marra et al. 2006) also make it clear that there was extensive use of thorium as a surrogate radionuclide to test glass varieties for vitrification of high-level waste sludge. At least two types of high-level waste sludge contained large amounts of thorium. Sludge type H modified high heat feed (HHF) contained 30,830 pounds of thorium and type H modified medium heat feed (HMF) contained 21,801 pounds (Peeler and Edwards 2003, Table 3-5, p. 10). NIOSH does not discuss whether there were any incident exposures during the handling and processing of sludge with large amounts of thorium.

NIOSH does not discuss incidents in other uses of thorium as a surrogate, notably in the HB-line. An investigation in the year 2000 concerned possible deflagrations and detonations in the HB-line:

> *Solutions of plutonium in nitric acid are purified and concentrated using anion resin prior to precipitation. There have been instances of resin column explosions caused by autocatalytic reactions of anion resins in nitric acid within the DOE complex. HB-Line applies controls to prevent these reactions… The effects of an explosion of plutonium-loaded columns on the public and the onsite workers have been evaluated and are within the evaluation guidelines. The effects on facility workers are being evaluated. Based on information on previous instances and tests run previously, the autocatalytic reactions may result in a deflagration, but do not cause a detonation in the columns.* [Hallman 2000, p. 1]

Thorium was used as a surrogate for plutonium-238 in the tests of the chemistry in the resin columns. Pressure was deliberately increased to make measurements that would simulate actual conditions. The paper does not explicitly discuss whether the autocatalytic reactions were carried to the point where deflagrations or explosions occurred. The paper refers to "previous instances and tests," indicating that the tests described were part of a process of reducing risks at SRS and put controls in place in the HB-line to prevent explosions. The paper also states that such controls were in place (Hallman 2000, p. 2).

NIOSH has not discussed this particular series of experiments in which thorium was used as a surrogate. It is important to investigate the routine exposure potential during the tests, as well as whether any incidents occurred while they were being conducted.

NIOSH has stated that it has not identified any thorium-related incidents in the Special Hazards Investigations database (NIOSH 2012, p. 22). However, this database is not a complete account of incidents at the SRS. An SRS site expert has pointed out (in an interview with ORAUT, NIOSH's contractor) that the database was created to record "incidents that seemed significant at the time…" ([**Redacted**] 2008).

NIOSH 2012 does not discuss thorium-related incidents beyond the mention of the Special Hazards database. Yet, one central reason that it resorted to the OPOS aggregation of bioassay data (see Sections 3 and 4 of this report) was to deal with multiple samples given by a single worker following an incident (NIOSH 2012, p. 28). Granted these incidents would be related to one of the trivalent radionuclides, but since NIOSH is proposing to interpret the data as thorium as well (depending on circumstances), a more detailed investigation of thorium incidents appears to be warranted. This is especially important for CTWs, since the SRS bioassay program for them appears to have been incident-oriented, according to NIOSH (see Section 3).

In some cases, NIOSH has explicitly noted that it lacks documentation to arrive at a quantitative estimate of the source term for thorium activities, as for instance in activities related to the Cassini program:

> *In July 1989 and April 1990, SRS received significant quantity shipments of thorium from ORNL (0.25 mCi) and LANL (0.017 mCi), most likely for use in the effort to assist LANL's production of the Cassini radioisotopic thermoelectric generators. All of the thorium was stored in Building 773A; the maximum quantity was 208 kg in February 1991.* ***NIOSH lacks documentation on how much of this inventory was used for Cassini program development*** *but, by December 1993, the thorium inventory had declined by 0.4 mCi and remained constant until February 1998 when the inventoried amount in Building 773A dropped to 0.4 mCi (4 kg). Using the inventory as the source, NIOSH concludes that SRS use of thorium in the Cassini program ended by December 1993, which is consistent with the SRS role of process development. A weld inspection report states that the development worked* [sic] *ended by April 15, 1993 (Welds, 1998).* [NIOSH 2012, p. 11, bolding added]

NIOSH's descriptions as well as SC&A's review indicate that thorium was used in varying amounts ranging from a few grams at a time to hundreds of grams at a time (for instance, in the use of thorium as a surrogate for plutonium-238 – see DuPont Monthly Report 1973, p. 12) to multiple kilogram quantities at a time [for example, in 1978 as part of the Thorium Fuel Cycle Technology Program (NIOSH 2012, pp. 9-10)].

NIOSH has tried to minimize the importance of various activities that used thorium by comparing the amounts involved in processing to the amounts that were stored and also to the amounts of other radionuclides at the site:

> *The activities [of various radionuclides]…were plotted in a bar chart... The activity of thorium (4.5 curies) is so small compared to activities of Cm-244 and Pu-238 that the bar for Th-232 is not noticeable. The activities for Th-232,*

> *Np-237, U-233 and Am-243 are shown in the blow-up chart. Even in the blow-up, the activity of Th-232 compared to Np-232* [sic], *U-233, Cf-252 and Am-243 is still barely noticeable. Table 5-4 and Figure 5-2 demonstrate that the activity of Th-232, and its associated radiological hazards, were insignificant compared to other radionuclides used and stored at SRS. Almost all of the thorium present was waste or spent fuel being held.* [NIOSH 2012, p. 16]

However, NIOSH's comparative discourse is beside the point. The issue is not radioactivity of thorium relative to that of other radionuclides. Rather, it is whether there was thorium exposure potential and, if so, whether thorium intakes can be estimated with sufficient accuracy with available data. Thorium was generally processed in far smaller amounts in terms of its radioactivity content than several other radionuclides at a variety of other sites. But it has been important in the context of SEC considerations nonetheless, because the data available to reconstruct thorium doses are far sparser, when they exist at all, than for many other radionuclides.

This issue of where and when thorium was handled and processed is especially important in the present context, because NIOSH proposes to use bioassay data for trivalent actinides (Am/Cm/Cf) to estimate thorium intakes. These worker bioassay data generally do not contain notations indicating thorium exposure potential or the places and times where there might have been such exposure. For instance, the individual worker records that we reviewed did not contain indications of thorium work areas or explicit thorium measurements in the 1972–2007 period, nor are there such indications in the coworker bioassay database compiled by NIOSH.

NIOSH's approach, as described in Addendum 3 of the ER, is rather vague. It simply states that the coworker model "will provide bounding thorium doses for SRS workers potentially exposed to the low-activity levels of thorium" (NIOSH 2012, p. 19). The ER also states that NIOSH would apply the "method for unmonitored workers…to SRS workers who had the potential for exposures to thorium" (NIOSH 2012, p. 31).

A NIOSH communication with SC&A (Makhijani 2013a) states the following:

> *Potential exposure to internal intakes of thorium was mostly limited to workers in Building 773-A. Coworker thorium intakes will be assigned to those who worked in Building 773-A.*

This seems a very limited scope; as we have seen above, thorium was handled in a wide variety of areas. Moreover, the times and places have not been fully covered by NIOSH in Addendum 3 of the ER.

As we shall see in more detail in Section 5.2, a scientifically reasonable estimation of dose from Am/Cm/Cf data requires knowledge of whether the worker was exposed to thorium or to one or more of the trivalent actinides. There are large differences in organ doses depending on the interpretation of the bioassay result.

Finally, the problem of radon-220 appears to be important in some areas. Specifically, a 1997 evaluation of two tanks in the H Area tank farm, Tank 12-H and Tank 15-H, had problems of radon-220 emanations. The amounts of thorium in these two tanks were 12,402 kilograms and 10,400 kilograms respectively (Sigg et al. 1997, Table 1, p. 18). NIOSH 2012 does not discuss the problems of radon-220 associated with thorium storage, even though storage of thorium continued through to 2007.

There are also indications of thoron exposures from residual thorium in a 1995 document:

> *During the 1960's the HM process in 221-H was used to recover U-233 from irradiated Th-232 (thorium) targets. A consequence of these campaigns is an increased level in the daughter products of Th-232, most notably Rn-220 (thoron). While thoron is a gas and has no significant interaction with matter, the thoron progeny is solid matter that can settle on materials and be collected on air sample filter papers. …*
>
> *Health Physics Technology (HPT) has recently completed evaluating other methods to assist in identifying thoron progeny on air sample filter papers. With this guidance, Radiological Control Operations (RCO) should be able to evaluate with greater confidence whether elevated air sample activity is due to thoron progeny or any of the long-lived alpha emitters.* [Epperson 1995]

This document mainly describes the issue of interpreting measuring stack sample data. However, there is a clear implication that residual thorium existed in the H-Canyon far beyond the time that irradiated thorium was processed for recovery of uranium-233. The implications of residual thorium as well as any thoron exposures resulting from it, for instance, to maintenance workers, needs to be investigated.

Table 1. SRS Thorium Activities from Late 1972 to 2007

Year	Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3				SC&A notes	
	Operations	Location	Total Inventory (kg)	Activity (mCi)	Notes	SRDB Ref
1972	storage, surrogate	773A, M Area (storage)	218	21.8	Oct 1972 SRS Monthly report discusses beginning of Pu-238 fuel form program in HB line. Radiation survey sheet 11/7/72: Thorium glovebox and apparatus from Lab 132 of 320M. Aug 1972 "A significant, unexpected quantity of thorium impurity was discovered in the ^{238}Pu prepared by reactor irradiation of Am and processed in the H-Area." Thorium contamination amounts were in the 2 to 4 gram range. April 1972 Leak in Tank 15H discovered from high thorium content tanks in H farm.	SRL 1972b SRL 1973 SRL 1972a Sigg et al. 1997.
1973	storage, surrogate	773A, M Area (storage)	218	21.8	Lab notebook of J. Watts in 735-A showed Th work during March and April 1973 for [Redacted] of 105-P.	Watts 1982
1974	storage, surrogate	773A, M Area (storage)	104	10.4	Thorium stored in 244-H June 1974 – April 1975. Thorium in 305-M Aug 1974- June 1975. May be storage only. Radiation survey log sheet for 2/6/74 mention ThO_2 in plastic bag in Lab 129 Bldg. 320M. May 1974 Leak in tank 12H discovered from high thorium content tank in H farm. Radon leakage concern (see 1997 item below).	SRL 1975a. SRL 1975b SRL 1975c Sigg et al. 1997.
1975	storage, surrogate	773A, 235-F, M Area (storage)	155	15.5	Lists thorium inventory "Trial balances" for July, Aug, Oct, Nov, and Dec 1975 in Areas 313M, 321M, 305M, K basin, RBOF, 235F, 321M, 723A, 777M, and 773A. Thorium stored in 244-H June 1974–April 1975. Thorium in 305-M Aug 1974–June 1975.	Thorium Balances 1975. SRL 1975a SRL 1975b

Table 1. SRS Thorium Activities from Late 1972 to 2007

Year	Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3				SC&A notes	
	Operations	Location	Total Inventory (kg)	Activity (mCi)	Notes	SRDB Ref
					Th inventory in works technical division Bldg. 723-A from Jan–Apr 1975.	Monthly Inventory Report 1975.
					Radiation survey log sheets 1/13/75 surveyed thorium billets in 107D in 235F.	SRL 1975f.
					Radiation survey log sheet for 2/3/75 surveyed 6 thorium balls in Room 125 of 322M.	SRL 1975c
					Radiation survey log sheet for 1/28/75 surveyed box of ThO_2 on 1st floor of 713A.	SRL 1975d
					Radiation survey sheet 5/23/75 of thorium tube from Room 123 of 322M.	SRL 1975e
1976	dissolution studies, storage, surrogate	773A, 235-F, M Area (storage)	135	13.5	Thorium inventories in Disassembly area of 100-K during March 1976 and Sept–Oct 1976. Appears to be storage only.	Thorium Cost 1976
1977	alternative fuels program, dissolution studies, storage, surrogate	773A, 235-F, M Area (storage)	116	11.6	Process technology for spent thorium fuel (Thorium Fuel Cycle Technology) scheduled to begin October 1977. Description only. Not clear from the document if process was implemented.	Driggers 1977
					Mr. [**Redacted**] began dissolution studies on thorium in Sept 1977 in actinide lab, room B-111 of Bldg. 773A. Most of the thorium stored in canisters in D wing of building. Interviews mentioned that "small quantities" of thorium were involved.	Smith and Chew 2012
					Incident report dated Feb. 1, 1977. Thorium contaminated scrap metal found in clean 740A salvage yard. Unclear what part of the contamination was thorium and what part was uranium.	Incident Report 1974–1983

Table 1. SRS Thorium Activities from Late 1972 to 2007

Year	Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3				SC&A notes	
	Operations	Location	Total Inventory (kg)	Activity (mCi)	Notes	SRDB Ref
1978	alternative fuels program, dissolution studies, storage, surrogate	773A, 235-F, M Area (storage)	92	9.2	March–December 1978 activities involving Thorium LWR Fuel cycle work. Throughput appears to be calculated rather than actual. Testing of the process was done that was described by NIOSH in the ER addendum (NIOSH 2012, pp. 8–10).	SRL 1978a, , SRL 1978b, SRL 1978c, SRL 1978d, SRL 1978e, SRL 1978f, SRL 1978g, SRL 1978h
					9 cells in high level caves of 773A prepped for Alternate Fuel cycle technology program.	SRL 1984b
					May 1978 memo listing thorium fuel stored at RBOF.	Thomas 1978
1979	alternative fuels program, tritium studies, storage, surrogate	773A, 235-F, M Area (storage)	125	12.5		
1980	alternative fuels program, tritium studies, storage, surrogate	773A, 235-F, M Area (storage)	157	15.7	November 1980 SRL began stocking thorium nitrate crystals in the 773A Chem Stores.	Thorium Inventory 1998
					December 1980 The quatrefoil-type assemblies are stored on a rack outside 786-A. All 30 rodlets are presently stored in a cage in Room C-070 in 773A.	Steimke 1980
					Thorium Irradiation Program planned through 1981 but terminated in December 1980; cycles planned for Aug, Oct, Dec 1980.	Cramer 1980
					Assemblies from Thorium Irradiation Program in P-reactor.	Pickett 1981

Table 1. SRS Thorium Activities from Late 1972 to 2007

Year	Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3				SC&A notes	
	Operations	Location	Total Inventory (kg)	Activity (mCi)	Notes	SRDB Ref
1981	alternative fuels program, welding agent studies, storage, surrogate	773A, 235-F, M Area (storage)	142	14.2	Welding studies may have started July 1981. December 1981 "Daughters of thorium have been detected by constant air monitors in E-063 after thorium solutions have been dumped to the high level drain in Cell #9. The problem is under study."	Folger 1982 Rinehart 1982
1982	welding agent studies, storage, surrogate	773A, 235-F, M Area (storage)	117	11.7	"Bench scale roasting and dissolution of ThO_2 and ThO_2/UO_2 reactor-grade ceramic pellets were studied at the Savannah River Laboratory to define the key parameters affecting dissolution." Report published January 1982. June 1982 thorium in Room C-070 773A, C-006, C-008. 65 kilograms of thorium material was transferred to the burial ground. Thorium quantities in 773A Chem Stores decreased to 2.9 kg in March 1982 to 2.7 kg in May 1982.	Pickett et al. 1981 SRL 1982 Thorium Inventory 1998
1983	welding agent studies, storage, surrogate	773A, 235-F	39	3.9	8/31/83 Th/depleted U oxide pellets to C-070 of 773A.	SRL 1983b
1984	welding agent studies, storage, surrogate	773A, 235-F	29	2.9	3/13/84 thorium moved from 23A-Room 8 of 773A to D110 of 773A. 3/17/84 thorium in room D-074 of 773A. Thorium inventory in 773A Chem Stores decreased to 1.2 kg in August 1984.	SRL 1984a SRL 1983a Thorium Inventory 1998
1985	welding agent studies, storage, surrogate	773A, 235-F	25	2.5	March 22, 1985, Thorium metal foil moved from lab C103 of 773A. March 28 1985 ThO_2 in Room D-07 of 773A.	SRL 1985 SRL 1985
1986	welding agent studies, storage, surrogate	773A, 235-F	12	1.2	Jan 1986 bottle of thorium found in room B-131 of 773A.	SRL 1986

Table 1. SRS Thorium Activities from Late 1972 to 2007						
Year	**Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3**				**SC&A notes**	
	Operations	**Location**	**Total Inventory (kg)**	**Activity (mCi)**	**Notes**	**SRDB Ref**
1987	welding agent studies, storage, surrogate	773A, 235-F	12	1.2		
1988	welding agent studies, storage, surrogate	773A, 235-F	24	2.4		
1989	welding agent studies, storage, surrogate	773A, 235-F	49	4.9		
1990	defense waste research, welding agent studies, storage, surrogate	773A, 235-F	214	21.4		
1991	defense waste research, welding agent studies, storage, surrogate	773A, 235-F	215	21.5		
1992	defense waste research, welding agent studies, storage, surrogate	773A, 235-F	213	21.3		
1993	defense waste research, welding agent studies, storage, surrogate	773A, 235-F	173	17.3	7/30/1993 memo from W.S. Loring to J.F. Jordan, Health Physics Technology was requested to assess the need for radiological controls on thoriated welding.	Loring 1993
1994	defense waste research, storage, surrogate	773A, 235-F	176	17.6		
1995	defense waste research, storage, surrogate	773A, 235-F	175	17.5	Elevated thoron progeny in 221-H. Thorium Purification of Scrap Pu-238 via Anion Exchange in HB-Line in H-Canyon from Sept 1995 monthly report.	Epperson 1995 WSRC 1995
1996	defense waste research, storage, surrogate	773A, 235-F	175	17.5		

Table 1. SRS Thorium Activities from Late 1972 to 2007

Year	Taken from NIOSH Table 5-3 of SEC-00103 Addendum 3				SC&A notes	
	Operations	Location	Total Inventory (kg)	Activity (mCi)	Notes	SRDB Ref
1997	defense waste research, storage, surrogate	773A, 235-F	175	17.5	Radon-220 emission concerns from tanks with high thorium content, specifically tanks 12-H and 15-H. Thorium content of each greater than 10,000 kilograms.	Sigg et al. 1997
1998	defense waste research, storage, surrogate	773A, 235-F	179	17.9		
1999	defense waste research, storage, surrogate	773A	175	17.5		
2000	defense waste research, storage, surrogate	773A	286	28.6		
2001	defense waste research, storage, surrogate	773A	286	28.6		
2002	defense waste research, storage, surrogate	773A	399	39.9		
2003	defense waste research, storage, surrogate, D&D	773A	299	29.9		
2004	defense waste research, storage, surrogate, D&D	773A	8	0.8	Personal air sampling data sheets for workers who had high exposures to thorium March–August 2004. Derived-Air-Concentration-hour data provided only for U, Pu, and Sr.	Hadlock 2004
2005	defense waste research, storage, surrogate	773A	7	0.7		
2006	defense waste research, storage, surrogate	773A	4	0.4		
2007	defense waste research, storage, surrogate	773A	4	0.4		

In summary, thorium was processed in several areas of the SRS in various processes in the 1972–2007 period. Given that the committed equivalent doses per unit intake due to the inhalation of thorium (Th-232) are significant for at least some organs, thorium needs to be considered in its own right at SRS, as it has been at other sites. For instance, the 50-year committed bone surface equivalent dose per Bq of Type M, AMAD 5 µm, thorium-232 inhaled is 1.5 mSv, a value which is higher than the bone surface dose coefficients of Type M, AMAD 5 µm Cm-244, Cf-252, or Am-241. We also show in Section 5.2 that knowledge of the specific radionuclide at issue (thorium or one of the trivalent actinides, Am, Cm, Cf) is important to estimating doses to either thorium or to Am/Cm/Cf in a scientifically reasonable manner. Finally, there was thoron exposure potential in some areas at least into the 1990s.

Finding 1: NIOSH has characterized various thorium storage and processing activities in its latest Addendum to the Evaluation Report (NIOSH 2012). However, NIOSH's catalog of places and times where such activities were carried out is not complete. A more complete description of the source term is needed for scientifically reasonable thorium dose reconstruction by the methods proposed by NIOSH.

Finding 2: Significant amounts of thorium were involved in some activities, such as using thorium as a surrogate for plutonium-238. NIOSH's argument that the amounts of thorium involved were far smaller than those of other radionuclides is not relevant to the feasibility of thorium dose reconstruction. Thorium-232 exposures need to be considered in their own right at SRS during the 1972–2007 period as they have been at other sites and at SRS during the period prior to October 1, 1972.

Finding 3: NIOSH's Addendum 3 to the Evaluation Report has not investigated thorium-related incidents beyond mention of the Special Hazards Investigations database, which is known to be incomplete. That database was not designed to be a comprehensive record of incidents. A more detailed investigation of thorium-related incidents appears to be warranted, especially since some of the bioassay data that NIOSH proposes to use are related to trivalent actinide incidents.

Finding 4: NIOSH has not discussed the radon-220 source term derived from the storage of thorium-232. The radon-220 dose could be important in some circumstances where there was a significant residual thorium or where thorium was stored in significant amounts. This includes at least two high-level waste tanks.

3.0 ONE PERSON-ONE-SAMPLE APPROACH AND ADEQUACY OF DATA FOR THE 1972–1989 PERIOD

NIOSH proposes to use the OPOS approach to aggregate bioassay data and use the aggregated data for constructing a coworker model for workers who do not have monitoring data. The monitoring data that NIOSH proposes to use are urinalysis data for the trivalent radionuclides, Am/Cm/Cf, interpreted as any of those three or as thorium-232 in a manner favorable to the claimant (NIOSH 2012, p. 28). The specifics of the OPOS approach for trivalent radionuclides were elaborated in ORAUT-RPRT-0055 (ORAUT 2012a).

SC&A has reviewed the general OPOS approach proposed by NIOSH in ORAUT-RPRT-0053 (ORAUT 2012b); that review can be found in SC&A 2013. We discuss a part of that review here; the full review provides a more detailed analysis.

3.1 GENERAL CONCERNS REGARDING THE USE OF OPOS DATA

One concern is that OPOS data understate the variability in individual bioassay data:

> ***Finding No. 3:*** *The OPOS statistic methodology summarizes a worker's exposure by averaging over all urine samples collected during the specified time period. The use of average values does not account for variability of the samples within the time period and the procedure will result in lower values of the GSD used in the coworker model.* [SC&A 2013, p. 20]

A second concern relates to whether a similar sampling protocol was followed in the monitoring of the two groups of workers being compared. SC&A found that the conclusions based on a comparison of the distributions for the two groups would not be valid if the sampling protocols were different:

> ***Finding No. 4:*** *The OPOS method must strictly be applied to comparisons where the sampling protocol was the same. Specifically, when there is evidence that the sampling protocol for one group of workers was different than the protocol used for the other group, the tests do not provide a valid comparison. For example, if the monitoring of one group of workers is incident-driven and the other is not, then the OPOS approach is not appropriate for comparing the two distributions.* [SC&A 2013, p. 22]

NIOSH itself has pointed out that the bioassay sampling protocols for CTWs and NCWs were different at SRS. In the report dealing with trivalent radionuclides, it noted:

> *CTWs are potentially subject to different bioassay practices than other workers. CTWs, many of whom are contractors, commonly submit bioassay samples after suspected uptakes and at the completion of jobs. This is in contrast to other workers, especially those employed directly by the prime contractor, who are more likely to be on a routine bioassay program in addition to submitting bioassay samples after suspected uptakes. A post-job bioassay is more likely to*

> *be soon after an unknown uptake than is a routine bioassay sample and thus would be higher. This potential difference in how the strata are monitored for intakes would result in higher results for CTWs compared to the other strata.* [ORAUT 2012a]

The different bioassay monitoring practices take on more significance in light of worker statements about the nature of CTW work. Some CTWs at SRS have stated in interviews documented by SC&A that their duties were often similar to those of NCWs, while others said their duties were different:

> *Some site experts indicated that CTWs don't work side by side with the operations personnel. CTWs have their work to do and operations personnel have their work to do. CTWs and operations may be in the same room, but not working on the same job. In the tritium facility, they worked more closely.*
>
> *In contrast, other site experts said CTWs worked side by side with site operations personnel on the same jobs. Typically, there was a mix of in-house and CTW personnel. For example, sometimes they had to pull out a heat exchanger weighing a hundred tons. There was a feed pump job on Tank 13 in H Area. The pump was about 20 ft long and 3 ft in diameter, and it sent high-level waste to the evaporator. It could be a rigger crane that pulled the pump, or CTWs could do it. There was a spill. Workers had to dig up the pavement around the tanks, with CTWs and operations working side by side. At other times, riggers were handling fuel rods that would be blue under the water. Everyone was being exposed. On a shutdown in B-line, there would be 100 pipefitters (construction workers) and 15 operators building huts and doing standby (assistance) for Construction. Site operators got to know the construction workers pretty well, because they worked as a team.* [SC&A 2012, p. 16]

The above quote indicates that whether CTWs did similar work as NCWs from time-to-time may have depended on the specific CTW job type. Whatever the specifics, it is clear from the above interview excerpt that CTWs were able to provide specific examples of work that they did when they worked side-by-side with NCWs. CTWs also stated that they were treated as "second class citizens" and often got the dirtier work in hotter areas (SC&A 2012, p. 17).

These considerations indicate that an emphasis on incident-related monitoring of CTWs may have missed routine exposures. As a result, CTW bioassay data in the 1972–1990 period may not reflect relative lack of routine exposure potential, but rather simply an assumption in the monitoring protocol about the relative lack of routine CTW exposure potential.

Finding 5: SC&A has concluded that NIOSH's method for comparing the measurements of two sets of workers requires that the monitoring protocols of the two sets of workers were the same. NIOSH has stated that the protocol for CTW bioassays was different. As a result, the method used by NIOSH to compare CTW and NCW Am/Cm/Cf data does not meet the requirements for a valid comparison of the two bioassay datasets for the 1972–1989 period.

Finding 6: NIOSH's coworker model for thorium is based on its conclusion that CTW and NCW bioassay samples are drawn from the same distribution. A corollary of Finding 5 above is that NIOSH's coworker model, which combines NCW and CTW data, is based on an invalid comparison and therefore is not suitable for estimating CTW thorium doses for the 1972–1989 period.

Finding 7: The SRS emphasis on incident-related monitoring of CTWs at SRS does not necessarily reflect differences between CTW work and NCW work. As a result, the emphasis on incident-related monitoring may have missed routine exposures for at least some CTW job types.

4.0 DATA ADEQUACY

SC&A reviewed and analyzed available electronic coworker database files developed by NIOSH for use in thorium dose reconstruction. Two main databases were compiled and provided by NIOSH and are located on the Centers for Disease Control (CDC) system O-drive (O:\Savannah River Site SEC\SRS databases for Coworker Models). The two available databases for the 1972–1989 period are as follows:

- *NOCTS Data OPOS R20.xlsx:* This database contains data that were obtained from the NIOSH/OCAS Claims Tracking System (NOCTS) and includes only claimant data. This data compilation was deemed insufficient for construction of a coworker model and is not discussed further in this review.
- *Am Final Compiled_SRS WHC_06302011r2_Ready Updated rev2.xlsx:* This database forms the basis for RPRT-0055 (NIOSH 2012a) according to the word document, "Description of databases used for the SRS internal coworker study_2013-02-15.docx" (NIOSH 2013), which is located in the same directory. This database is discussed and analyzed in Section 4.1.

The analysis of the second database, which forms the basis for RPR-0055, looks at the total number of NCW OPOS results by year (or other specified time-period) as well as the number of available results that specifically represent CTWs. Additionally, the number of positive results (defined as above the minimum threshold of detection) for each group (NCWs and CTWs) is compiled. A brief discussion of the specific job titles of "Pipefitter" and "Laborer" is also included for each database reviewed in Section 4.2.

4.1 ANALYSIS OF COWORKER DATABASE USED IN RPRT-0055

This section reviews the NIOSH coworker database titled, "Am Final Compiled_SRS WHC_06302011r2_Ready Updated rev2.xlsx,"[1] which can be found in the directory O:\Savannah River Site SEC\SRS databases for Coworker Models. ORAUT 2013 states the following concerning this database:

> *RPRT-0055 Data (Spreadsheet is called "Am Final Compiled_SRS WHC_06302011r2_Ready Updated rev 2.xlsx")*
>
> *Insufficient Am/Cm/Cf data was available for the time period prior to 1991 in the NOCTS bioassay database. Therefore, Am/Cm/Cf data was retrieved from handwritten SRS logbooks for the period from 1963 through 1989. This data was compiled into a spreadsheet for use in the coworker study. The format of the spreadsheet matches the format used in the logbooks. This spreadsheet also contains the information from the worker history cards.*

[1] Note: an additional spreadsheet exists titled, "Am Final Compiled_SRS_WHC_06302011r2_OPOS analysis R10 CTW nonCTW unk strata %s.xlsx," which contains the OPOS data derived from this database.

An overview of the OPOS results compiled from this database is shown in Table 2. As seen in the table, there were well over 200 OPOS results for each period of interest established by NIOSH. For most of these time periods, approximately 10% to 20% of the OPOS results were attributed to CTWs, except for the period from 1984 onwards, when it was less than 10%, and just 6.3% during 1987–1989, for which NIOSH has provided combined OPOS results. In compiling the data shown in Table 2, SC&A attributed the term "positive" to mean any OPOS result that was greater than or equal to the MDA value of 0.3 dpm/1.5 L. All results with a value "<0.3" in the "Report" column were treated as censored data.[2]

Table 2. Overview of Available OPOS Results Compiled for RPRT-0055

Year	Total # of NCW OPOS Results (% of Total OPOS)	Total # of CTW OPOS Results (% of Total OPOS)	Total Positive NCW OPOS Results (% of NCW Total)	Total Positive CTW OPOS Results (% of CTW Total)
1972 (Full Year)	525 (80.6%)	110 (16.9%)	33 (6.3%)	7 (6.4%)
1972 (Oct–Dec)	228 (84.1%)	37 (13.7%)	6 (2.6%)	3 (8.1%
1973	509 (78.9%)	115 (17.8%)	13 (2.6%)	4 (3.5%)
1974	357 (78.1%)	86 (18.8%)	16 (4.5%)	0 (0.0%)
1975	356 (75.9%)	94 (20.0%)	11 (3.1%)	4 (4.3%)
1976	346 (76.9%)	90 (20.0%)	11 (3.2%)	1 (1.1%)
1977	292 (76.2%)	68 (17.8%)	5 (1.7%)	1 (1.5%)
1978	171 (75.0%)	49 (21.5%)	27 (15.8%)	6 (12.2%)
1979	234 (72.7%)	67 (20.8%)	35 (15.0%)	10 (14.9%)
1980	178 (77.4%)	42 (18.3%)	2 (1.1%)	3 (7.1%)
1981–1982	379 (81.3%)	44 (9.4%)	16 (4.2%)	5 (11.4%)
1983	232 (76.6%)	39 (12.9%)	5 (2.2%)	0 (0.0%)
1984	210 (76.4%)	20 (7.3%)	3 (1.4%)	3 (15.0%)
1985	214 (82.6%)	24 (9.3%)	7 (3.3%)	1 (4.2%)
1986	219 (80.2%)	26 (9.5%)	2 (0.9%)	1 (3.8%)
1987–1989	336 (84.8%)	25 (6.3%)	14 (4.2%)	0 (0.0%)

Table 2 shows that there were less than the minimum 30 results required for a valid CTW-NCW comparison in each aggregated period during 1984–1989. This means that NIOSH does not have adequate data on which to base its conclusion that CTW and NCW samples are drawn from the same distribution for the 1984–1989 period. Furthermore, NIOSH has aggregated data for 1981–1982; this yields 44 CTW data points for the period. However, the number of data points on an annual basis would be lower. It is unclear why NIOSH has chosen to aggregate data over more than 1 year for the two periods 1981–1982 and 1987–1989, but not in other cases. It may have been to increase the number of data points in those years. However, SC&A does not consider this a technically or statistically valid reason, since this would allow aggregation of data over periods without limit, without reference to working conditions, process changes, periods during which thorium was processed and periods when it was not, and the intensity of those activities.

[2] NIOSH has not used the data in this way. NIOSH's interpretation of the raw data to compile OPOS results is extensively discussed in Section 4.2.

By SC&A's count, 1981 has 34 OPOS values, while 1982 has only 18. The latter number is inadequate for a valid CTW-NCW comparison.

A further complication of aggregating results over long periods of time for estimating OPOS values in the specific instance of a thorium coworker model is that it increases the chance that exposures to trivalent actinides and thorium would be mixed up in the same OPOS result. Such results would have no practical utility for dose reconstruction, as is discussed in Section 5.2.

Finding 8: The number of CTW data points is less than 30 in each aggregated period during 1984–1989. This is less than the minimum number required for a valid comparison between CTWs and NCWs. Therefore, NIOSH's conclusion that CTW and NCW sample distributions are the same is not valid for this period. As a result, the coworker model based on this conclusion has not been shown to be valid for this period.

Finding 9: While NIOSH has not provided disaggregated data for 1981 and 1982, the number of CTW data points for 1982 is less than 30. Hence, the data for 1982 are also insufficient for a CTW-NCW distribution comparison.

Finding 10: Aggregating data over more than 1 year without reference to underlying processes and other data is not justifiable. NIOSH should provide a technical rationale for treating 1981–1982 and 1987–1989 differently than other years. Aggregation over more than 1 year to increase the number of data points is not a suitable technical rationale. If no sound basis can be provided for aggregating data over more than 1 year, NIOSH should do annual aggregating for calculating OPOS values. This is important for evaluating NIOSH's conclusion that CTW and NCW data are drawn from the same distribution. Furthermore, aggregation over multiple years rather than a single year to estimate an OPOS value increases the risk that the result would represent a mix of thorium exposure and Am/Cm/Cf exposure, rendering it scientifically questionable.

4.1.1 Type 1 and Type 2 Error Rates and Number of Measurements Needed – Theoretical Example

SC&A agrees with NIOSH that 30 samples in each worker category is a necessary minimum for a comparison of the distributions of the data for two worker categories. But it may or may not be sufficient. It is important to explore the constraints imposed by the specific datasets on the comparison to make determination whether a given number of samples are adequate. Specifically, data requirements increase under certain circumstances.

Specifically, the rate of Type 2 errors, defined as a failure to reject the null hypothesis that the distributions are the same, rises with an increasing GSD for a given ratio of CTW to NCW GMs. The Wilcoxon Rank Sum (WRS) test was used to determine the Type 2 error rate for a given Type 1 error rate (defined as a failure to accept the null hypothesis when it is true). We applied this test to a test case when both groups of workers had 30 samples each and a fixed ratio of GMs. The results are described in this section. In Section 4.1.2, we describe results with actual SRS trivalent actinide bioassay data and varying numbers of samples for NCWs and CTWs in various years.

Table 3 shows the results of the WRS test for relatively small fractions of non-detects. When the number of results below MDA is low, Type 2 errors are less than 15% only when the GSD is less than about 4 (maintaining Type 1 errors at 5%). Low rates of Type 2 errors (less than 10% or 15%) at high GSDs can only be achieved at the expense of increasing Type 1 errors (incorrectly rejecting the hypothesis that the two distributions are the same). This is shown in Table 4, where a hypothetical illustration with each group having 30 samples is provided. **Note that it is the relationship of the ratio of the CTW to NCW GMs to the GSD for NCWs that is important**. We set the GM_{CTW}/GM_{NCW} ratio to 2.73 in all the above calculations in order to clearly illustrate the role of varying GSDs.

The problem of rising Type 2 errors at a given level of Type 1 error is exacerbated when the number of non-detects is high. Table 4 shows the results when the fraction of below MDA results is high (in the 67% to 84% range).

Table 3. Type 2 Error Rate (β) of the WRS Test using 30 Samples from Lognormal Distributions with a Low Detection Limit for Selected Values of Alpha

($n_1=n_2=30$ and $GM_2/GM_1 = 2.73$)

Low LOD=0.5	GSD					
α	7	6	5	4	3	2
0.05	0.416	0.351	0.269	0.161	0.043	< 0.001
0.10	0.280	0.221	0.161	0.085	0.019	< 0.001
0.20	0.150	0.113	0.073	0.035	0.006	< 0.001
0.25	0.118	0.090	0.054	0.024	0.003	< 0.001
% Nondetects	28	26	24	21	16	8

Note: Shaded area indicates cases with β < 0.15 (i.e., a Type 2 error rate of < 15%).
Source: Attachment C, Table 1.

Table 4. Type 2 Error Rate (β) of WRS Test using 30 Samples from Lognormal Distributions with a High Detection Limit for Selected Values of Alpha

($n_1=n_2=30$ and $GM_2/GM_1 = 2.73$)

High LOD=4.0	GSD					
α	7	6	5	4	3	2
0.05	0.525	0.477	0.413	0.328	0.194	0.054
0.10	0.376	0.330	0.276	0.203	0.107	0.021
0.20	0.223	0.191	0.151	0.098	0.045	0.007
0.25	0.179	0.144	0.109	0.071	0.030	0.004
% Nondetects	67	68	70	73	77	84

Note: Shaded area indicates cases with β < 0.15.
Source: Table 2, Attachment C.

4.1.2 Type 2 Error Rates in Selected Years using Actual Data but a Hypothetical Decision Level

SC&A attempted to apply this analytical approach to examine the adequacy of available data in four of the years when the total number of CTW samples exceeds 30. We chose the years 1974,

1976, 1977, and 1983 to apply the method illustrated in Section 4.1.1 to the available trivalent radionuclide monitoring data for NCWs and CTWs.

We tried to determine the number of CTW OPOS values in each year above the MDA for this analysis. However, there are no OPOS values greater than the MDA of 0.30 dpm per 1.5 L in 1974, 1983, and 1987–1989, and only one OPOS value above that in 1976 and 1977. The remaining years have a small number of values over the MDA, but no year has more than 10 (see Table 2). This makes an analysis using the MDA as the cutoff difficult since there are not a sufficient number of points above the MDA to estimate a lognormal GM and GSD.

Internal dosimetry practice also uses a "decision level" (DL) that is below the MDA (see the equations for these parameters on pp. 10-10 and 10-11 of Internal Dosimetry 2001). A hypothetical DL of 0.10 dpm per 1.5 L was selected to conduct the analysis since it provided a sufficient number of values over the DL to estimate a GM and a GSD for each group of workers in each year. We stress that this value is used for illustrative purposes only to bind the data into "greater than or equal to" and "less than" categories. The purpose is to examine the sensitivity of the error rates to varying GM ratios and GSDs based on actual CTW and NCW trivalent radionuclides data for the 1972–1989 period.

A simulation was conducted to estimate the power of the WRS test using lognormal distributions with the estimated GMs and GSDs in 1974, 1976, 1978, and 1983. Table 5 shows the number of samples for NCWs and CTWs in each of these 4 years. The number is greater than 30 in all cases.

Table 5. Number of NCW and CTW samples in 1974. 1976, 1978, and 1983

Year	Number of NCW samples	Number of CTW samples
1974	357	86
1976	346	90
1978	171	49
1983	232	39

The simulation results for 1974, 1976, 1978, and 1983 are summarized in Table 6. The Type 1 error is controlled at 5% in all cases. In other words, for all the results shown, the probability of incorrectly rejecting the hypothesis that the distributions are the same is kept at 5%. We are testing for the probability that this hypothesis will be incorrectly accepted—that is, the probability that we will incorrectly conclude that the two distributions are the same when they are not. We can conclude with high confidence that the distributions are the same when both errors are low. In the present case, the Type 1 error is maintained at 5%, and is low by the nature of the test.

The first column shows the ratio of the GMs of the two groups of workers (GM_{CTW}/GM_{NCTW}). This ratio is a measure of the difference in location of the two distributions. All ratios in this column are greater than 1 and the CTW distribution has a higher GM than the NCW distribution in each of these 4 years. Whether the test can detect this difference depends on two factors: the ratio of the GMs (*delta*) and the magnitude of the variability (GSD) in the datasets (*sigma*). The GM ratio is used here as a measure of the size of the difference (*delta*). We use the GMs of the

two GSDs,[3] which are shown in the second column. This term (*sigma*) is used as a summary measure of the variability in the two datasets. The ratio of delta to sigma is shown in the next column. A small value of *delta/sigma* indicates that it will be difficult to resolve the difference in the two distributions because the GM difference is small relative to the variability. When *delta/sigma* is large, the difference is more easily detected, because the GM difference is large relative to the variability. The years with smaller values of *delta/sigma* are expected to have larger Type 2 errors, and vice versa.

The final columns show the simulation results. The probability of accepting the null hypothesis when it is not true is called a Type 2 error and is shown in the fifth column. The final column shows the probability of rejecting the null hypothesis. This is the correct test outcome, since the GM of the CTWs exceeds the GM of the NCWs in all 4 years. The Type 2 error rate is low in 1974 and 1983, years with the two highest values of *delta/sigma* (3.6 and 1.5). The Type 2 error rate is very high in 1976 and 1978, years with the lowest *delta/sigma* ratios (0.9 and 0.3).

Table 6. Summary of Simulation Results for 1974, 1976, 1978 and 1983

Year	GM Ratio (CTW/NCW) (delta)	GM of GSDs (sigma)	delta/sigma	Probability of Accepting Null when it is not true (%) (Incorrect Decision, Type 2 Error)	Probability of Rejecting Null when it is not true (%) (Correct Decision)
1974	19.9	5.5	3.6	7.6	92.4
1976	3.1	3.4	0.9	80.7	19.3
1978	1.5	4.5	0.3	97.4	2.6
1983	3.7	2.4	1.5	2.3	97.7

Figure 1 shows the comparison of the test outcomes in the 4 years graphically. In this figure, the years are ordered in terms of the *delta/sigma* ratio. Years with a high *delta/sigma* show a high rate of correct decisions (right bar) and a corresponding low rate of incorrect decisions (left bar), and vice versa. The smallest delta/sigma ratio, 0.3, is in 1978. In that year, the probability of incorrectly accepting the null hypothesis is very high—greater than 90%. The Type 2 error is also very high—above 80% in 1976. It is low in both 1974 and 1983.

In summary, our examples show that it is essential to examine the Type 2 error rate even when the number of samples is above 30. Indeed, our case studies for these years show that the number of CTW samples is a less important parameter than the delta/sigma ratio, provided the number of samples is greater than 30. For instance, the Type 2 error rate is lowest in 1983, when the number of CTW samples is the lowest of the 4 years (at 39), but the delta/sigma ratio was high (1.5). The year 1976 had 90 CTW samples, but a low delta/sigma ratio; the Type 2 error rate was above 80%.

[3] The GM of the two GSDs = SQRT(GSD_{CW}*GSD_{NCW}).

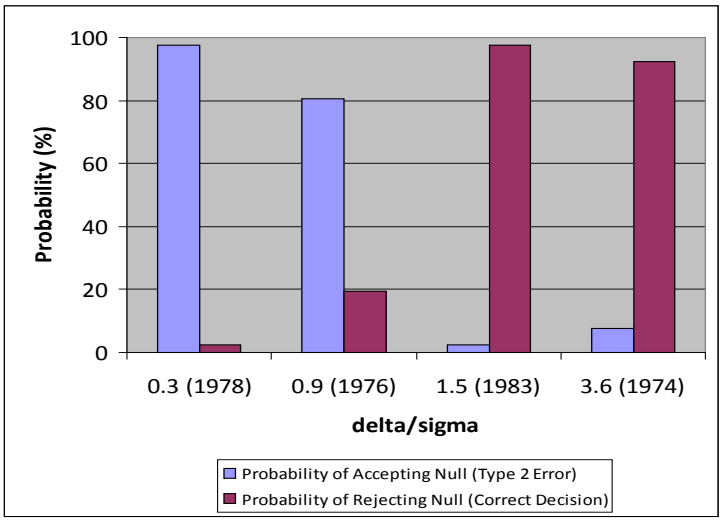

Figure 1. Summary of Simulation Results for 1974, 1976, 1978 and 1983

Finding 11: NIOSH has not demonstrated that the number of CTW samples is sufficient to simultaneously maintain low levels of Type 1 and Type 2 errors (for instance, less than 5% for Type 1 errors and less than 15% for Type 2 errors) even in the years when CTWs have more than 30 samples. SC&A's analysis indicates that when the geometric standard deviation (GSD) is much larger than the ratio of CTW to NCW geometric means (GMs), the rate of Type 2 errors will tend to be high. Type 2 errors occur when the null hypothesis (distributions are the same) is incorrectly accepted.

Finding 12: In some years, the number of data points is inadequate to make a valid comparison between CTWs and NCWs in regard to trivalent actinide data distributions, even when there are more than 30 data points. In other cases, there are sufficient data. NIOSH has not analyzed the problem of data adequacy as a function of relative GM and GSD values. Such an analysis is essential for evaluating data adequacy for comparing CTW and NCW distributions.

4.2 MINIMUM DETECTABLE ACTIVITY AND CENSORED RESULTS

SC&A could not make a definitive analysis of the problem of the number of CTW samples that would be needed in each year because NIOSH does not use any specific value for censoring the data. SC&A sent an inquiry on this matter to NIOSH (Makhijani 2013b).

In the analysis in Section 4.1, we used 0.1 dpm/1.5 L as the level at which the data would be censored. As noted, this is a hypothetical value. Since it was unclear what level NIOSH was using, SC&A sent the NIOSH staff an e-mail inquiry. NIOSH's response raises a host of questions about the statistical basis of the OPOS data—whether it is scientifically reasonable or claimant favorable, and whether it is in conformity with normal NIOSH dose reconstruction practices for individuals.

Specifically, NIOSH responded as follows:

> *Uncensored results can be above or below the MDA and are used in the averaging at face value, whether negative, positive, >MDA, or <MDA. Being above or below the MDA has nothing to do with whether the value is censored. Per ORAUT-RPRT-0053* [ORAUT 2012b], *an OPOS result for an individual is treated as an uncensored value if any of the results averaged together are uncensored. The OPOS result is treated as a censored result only if all the results averaged together are censored.*
>
> *Censored results tend to be censored at the MDA, which is where the confusion may begin. A censored result is assumed to be equal to the MDA value (or the value at which the result is censored, if different) for the purposes of averaging. <MDA values are assumed to be equal to the MDA only if they are reported as "<" values, i.e., censored. If an actual value is reported that is below the MDA, then that actual value is used.*
>
> *In summary for OPOS methodology, we use values both above and below the MDA because we believe that for averaging purposes all of the analytical information available should be used.* [Makhijani 2013b]

In SC&A's view, there are two levels at which data could be censored for estimating the "Maximum Possible Mean" in the OPOS methodology:

(1) The MDA
(2) The DL, which is generally less than the MDA (see Internal Dosimetry 2001, pp. 10-10 and p. 10-11).

It is clear from the NIOSH e-mail quote above that NIOSH uses neither. Rather, NIOSH takes calculated numbers from logbooks at face value for averaging, even when the logbook entry under the term "Report" is a censored value. Using this process, NIOSH includes in their average arithmetically negative values and zeros.[4] There are a number of problems with this approach to estimating averages that are meant for dose estimation.

First and fundamentally, this method can yield scientifically meaningless results in some cases. Consider, for instance, an employee with 1 year of data and all zero or negative results. Taking the reported result at face value would result in a negative radiation dose—obviously a scientifically meaningless result.

To gain perspective on the prevalence of "negative" OPOS results, SC&A compiled the number of such results by year and by job classification. This is shown in Table 7.

[4] Negative values are not in themselves wrong. The calculated result is sometimes negative because the values are net of background. When the gross counts are less than the background, a negative number results. Counts for both the analyte and the tracer are taken into account. See equations for A (activity being measured) and R (fraction of the tracer recovered) in Internal Dosimetry 2001 on p. 10-10.

Table 7. Number of "Negative" Calculated OPOS Results by Time Period

Time Period	# Negative OPOS Results (% of Total OPOS Results)	
	NCW	CTW
1972–1974	0 (0.0%)	0 (0.0%)
1975	15 (4.2%)	4 (4.3%)
1976–1980	0	0
1981–1982	1 (0.3%)	0 (0.0%)
1983	92 (39.7%)	13 (33.3%)
1984	112 (53.3%)	9 (45.0%)
1985	120 (56.1%)	6 (25.0%)
1986	162 (74.0%)	15 (57.7%)
1987–1989	14 (4.2%)	0 (0.0%)

As seen in Table 7, the observed negative OPOS values were mostly restricted to the 1983–1989 timeframe, with some negative values also observed in 1975 and 1981–1982. The 1983 to 1986 period showed the highest incidence of negative OPOS values. In 1986, nearly three-fourths of all OPOS results for NCWs were negative.

In two instances, large negative OPOS values were reported; one OPOS CTW result was -69.73 dpm/1.5 L (in 1983) and one OPOS NCW result was -73 dpm/1.5 L (in 1984). SC&A believes these numbers may contain transcription or interpretation errors of the raw data. The former OPOS value, for instance, contains a raw data point equal to -210 dpm/1.5 L. They are so large in negative territory as to render the arithmetic average of all OPOS results for those worker categories negative for those years. Indeed, in the case of the 1983 result, the arithmetic average of all NCW and CTW OPOS results is negative.

Second, even when there are no negative or zero reported results, taking values below some minimum, such as the DL or MDA, at face value, would yield dose estimates that are systematically claimant unfavorable. The problem even affects many of those cases that had one of the measurements on a urine sample that was above the MDA. By SC&A's count, 54% of the urine samples that contained an above MDA measurement also had a below MDA measurement that was included in the sample average.

In recognition of the problem of below MDA measurements, it is standard practice for NIOSH to use a value of MDA/2 as the expected value of the bioassay when the reported result is below the MDA in individual dose reconstructions (ORAUT 2007, OCAS 2002). Specifically, NIOSH's internal dose reconstruction procedure prescribes the following methods that involved the use of a value of half the detection limit:

> *To calculate a missed dose, a chronic intake throughout the possible exposure period is assumed.*
>
> *The specific dates can vary depending on the bioassay method's MDA over time.*
>
> *If the detection threshold changes through the intake period, the following must be considered in determining the chronic intake:*

- *If the detection threshold decreases over time and the radionuclide/absorption type reaches equilibrium slowly in the compartment of interest (e.g., in urine: Type M or S plutonium/ transuranics or Type S uranium), perform the fit using the date of the last sample* ***and half of the associated detection threshold,*** *assuming a single chronic intake for the entire potential exposure period.*
- *If the detection threshold decreases over time for radionuclide/absorption types that reach equilibrium rapidly, or if the detection threshold increases over time, use IMBA to determine chronic intakes applicable to each period…*

  …

  – ***Perform the fit assigning half of the associated detection threshold*** *to the date of the last sample in each period.*
  [ORAUT 2007, p. 15] [Emphasis added]

The basic NIOSH internal dosimetry guideline, issued as far back as 2002 to provide dose reconstruction guidance, describes a claimant-favorable approach ("likely a high estimate") when "there is a large deficiency of information." It prescribed "a target value that is ½ the detection limit (LD-1.645*0.3*LD = 0.5*LD)" (OCAS 2002, p. 32). This is not as claimant favorable as the approach in the more recent external dose guidance for readings less than the limit of detection (LOD) (see Section 4.2.1), but still a technically defensible way of handling less than MDA data.

The NIOSH internal dose reconstruction procedure also specifies a complex approach to the use of deterministic values that are less than MDA or the LOD in the dosimetry record. The MDA is entered into the software for estimating dose, but the number of times it is entered is limited, so that repeated MDA results do not dilute the weight of above MDA results:

> *In IMBA, for results <MDA, Measurement Result = MDA value, Data Type = "<LOD." Include the first negative (<MDA) result following each set of positive results. If there are multiple positive results, include no more than two negative results. For fewer than five consecutive positive results, include only one negative result.* ***Use of additional "<LOD" results, particularly for chronic exposures, frequently yields a fit that appears to underestimate the general trend of the data.*** *Note that the presence of a result less than the MDA does not mean that a new intake must be assigned for the next result greater than the MDA.* [ORAUT 2007, p. 12] [Emphasis added]

In the above quote, NIOSH actually uses the term "negative results" to mean results that are less than the MDA, rather than arithmetically negative results. Entering the MDA in the input data for below MDA results in the way described in the above quote will result in the software assigning a distribution to the below MDA results that would not extend to arithmetically negative numbers, since lognormal or triangular distributions are normally used; it would be expected to yield technically reasonable results.

There are some cases where the internal dose reconstruction procedure allows the use of a <MDA result as a measured result. This is in the context of many positive results:

> *If the **majority of results are positive and scattered throughout the intake period (with no more than a few consecutive <MDA results), use all results to do the intake assessment.** If the data are not censored (results <MDA are recorded as measured rather than as a "<" value or as the MDA), enter the result as recorded with a Data type = Real. Otherwise, enter the MDA for the value and mark it <LOD.* [ORAUT 2007, p. 13] [Emphasis added]

Results that are not "censored" (i.e., below MDA recorded as real results) are only to be used when most results are positive throughout intake period. This does not describe SRS trivalent actinide urine data, where the vast majority of results are below the MDA. As a result, the above ORAUT 2007 guidance that would permit <MDA data at face value is not applicable to the SRS trivalent actinide dataset.

There is no guidance in ORAUT 2007 about the use of values that are arithmetically less than zero.

SC&A has reviewed a large number of dose reconstructions and has found that the use of MDA/2 when the bioassay result is below the MDA is standard practice. SC&A can provide examples to the Work Group or NIOSH if that should be deemed desirable or necessary.

To illustrate the above points, SC&A compiled the logbook data, the data in the worker records sent by the Department of Energy (DOE) to NIOSH, and the OPOS value calculated by NIOSH for five workers.[5] The data are shown in Tables 8 through 12.

Table 8. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5 L) versus DOE-Supplied Claimant Records, Case 1

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result	Value Supplied in DOE Records
2/6/1973	0.017	<0.3	0.094	<0.3
7/12/1973	0.23, 0.111	<0.3		<0.3
1/15/1974	0	<0.3	0.07	<0.3
9/18/1974	0, 0.27	<0.3		<0.3
1/27/1975	0.038, 0	<0.3	0.010	<0.3
7/10/1975	0	<0.3		<0.3
5/3/1976	0	<0.3	0	<0.3
7/12/1976	0	<0.3		<0.3
11/4/1977	0.046	<0.3	0.046	Not Found

[5] There are claims for all five workers and therefore the data are available in NIOSH's database called NOCTS. Claim numbers have been removed in this report to protect privacy, but can be supplied to the Board and NIOSH.

Table 9. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5 L) versus DOE-Supplied Claimant Records, Case 2

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result	Value Supplied in DOE Records
2/7/1973	0.026	<0.3	0.009	<0.3
7/12/1973	0	<0.3		<0.3
10/15/1973	0	<0.3		<0.3
1/28/1974	0	<0.3	0	<0.3
7/8/1974	0	<0.3		<0.3
1/9/1975	0.078	<0.3	0.069	<0.3
7/8/1975	0.06	<0.3		<0.3
1/7/1976	0	<0.3	0	<0.3
4/11/1977	0	<0.3	0	<0.3
5/18/1978	0.371, 0.309	0.3[6]	0.34	0.3
8/7/1984	-0.037	<0.3	-0.037	<0.3

Additional note: Claimant DOE files contain additional bioassay results attributed to different Payroll ID#. These were considered two separate workers in the OPOS calculation.

Table 10. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5L) versus DOE-Supplied Claimant Records, Case 3

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result	Value Supplied in DOE Records
1/23/1973	0, 0.129, 0.009	<0.3	0.062	<0.3
1/25/1973	0, 0.111, 0, 0, 0.171, 1.3	<0.3		<0.3
5/19/1973	0, 0	<0.3		<0.3
8/15/1973	0, 0	<0.3		<0.3
11/19/1973	0, 0	<0.3		<0.3
5/6/1974	0.027	<0.3	0.0135	<0.3
11/4/1974	0	<0.3		<0.3
4/29/1975	0.163	<0.3	0.054	<0.3
5/5/1975	0	<0.3		<0.3
11/11/1975	0	<0.3		<0.3
4/6/1976	0	<0.3	0.029	<0.3
11/4/1976	0, 0.116	<0.3		<0.3
7/18/1977	0	<0.3	0	<0.3
6/13/1978	0	<0.3	0	<0.3
5/6/1980	0.047	<0.3	0.047	<0.3

[6] The "Remarks" column in the logbook contains "0.34," several other entries in this logbook have the "Report" values carried out to two decimal places.

Table 11. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5 L) versus DOE-Supplied Claimant Records, Case 4

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result	Value Supplied in DOE Records
2/21/1973	0.017	<0.3	0.009	<0.3
8/16/1973	0	<0.3		<0.3
2/11/1974	0.079	<0.3	0.04	<0.3
8/29/1974	0	<0.3		<0.3
2/13/1975	0	<0.3	0	<0.3
8/5/1975	0	<0.3		<0.3
3/16/1976	0.058	<0.3	0.029	<0.3
8/9/1976	0	<0.3		<0.3
8/14/1977	0	<0.3	0	<0.3
6/14/1978[7]	0	<0.3	0	<0.3
5/7/1979	35.932, 0	72	17.966	<0.3

Table 12. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5 L) versus DOE-Supplied Claimant Records, Case 5

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result[8]	Value Supplied in DOE Records
1/17/1973	0.626, 0.454	0.5	0.517	0.5
1/18/1973	0.737, 0.711, 0.943, 1.217	0.9		0.9
1/19/1973	0.111, 0.257, 0.257, 0.394, 0.291	0.3		0.3
2/21/1973	0.531, 0.737, 0.617, 0.711	0.6		0.6
5/7/1973	0.163, 0.11	<0.3		<0.3
5/21/1973	0.094, 0.334	<0.3		<0.3
8/13/1973	0.89, 1.17, 0.69	0.9		0.9
2/11/1974	0.063, 0.06	<0.3	0.098	<0.3
5/3/1974	0, 0.518, 0.101, 0.269	<0.3		<0.3
8/9/1974	0.102	<0.3		<0.3
11/8/1974	0.016, 0	<0.3		<0.3
2/21/1975	0.009, 0.067	<0.3	0.04 (note 1) 0.094	<0.3
5/6/1975	0.085	<0.3		<0.3
8/5/1975	0	<0.3		<0.3
9/29/1975	0.188	<0.3		Not Found
11/17/1975	0	<0.3		<0.3
8/23/1976	0.181, 0.143	<0.3	0	<0.3
11/11/1976	0	<0.3		<0.3
5/13/1977	0	<0.3	0	<0.3
2/28/1978	0,0, 0, 0.111	<0.3	0.163	<0.3
6/27/1978	0.759, 0.405, 0.187, 0.861	0.6		LIP
12/13/1978	0.481, 0.115	<0.3		Not Found
2/27/1979	0.68	Blank	0.385 (note 1) 0.067	Not Found
6/7/1979	0.09	<0.3		Not Found
11/20/1979	0.067	<0.3		<0.3
7/21/1980	0.239	<0.3	0.159 (note 1)	<0.3

[7] Incorrectly transcribed, this date should be 6/14/1979 and included in the 1979 estimate.

[8] Note: there are two OPOS results for some years because this worker had 2 payroll IDs, each payroll ID was treated as a separate worker for OPOS calculations.

Table 12. Detailed Comparison of Logbook Urinalysis Results (dpm/1.5 L) versus DOE-Supplied Claimant Records, Case 5

Sample Bottle Date	Logbook Raw Result(s)	Logbook "Report" Result	NIOSH-Calculated OPOS Result[8]	Value Supplied in DOE Records
7/22/1980	0.006, 0.12, 0.04, 0.458	<0.3	0	<0.3
7/22/1980	0, 0.073, 0, 0.443	<0.3		<0.3
7/22/1980	0.111	<0.3		<0.3
7/24/1980	0	<0.3		<0.3
5/20/1981	0	<0.3		<0.3
12/17/1981	0	<0.3		<0.3

Note 1: In this case, the same worker had two identification numbers, each with its own samples. NIOSH calculated OPOS values for each identification number. The values shown are as calculated by NIOSH.

These examples uniformly illustrate some problems. First, the values in the individual worker records supplied by the DOE are the same as those in the "Report" column of the logbooks. These are the values used in dose reconstruction. Whenever the calculated result was less than the MDA of 0.3 dpm/1.5 L, the "Report" column value in the logbook and the value in the worker file entered at the time of analysis was always "<0.3"; i.e., it was entered as a censored value. NIOSH has ignored these censored values in the logbooks to calculate its OPOS values. In several cases, the resultant OPOS value is zero. In one case, the last value in Table 9 is negative.

We also note that the logbooks never report an average value of several measurements on the same day that is less than the MDA as an uncensored number. For instance, there were four values calculated on the same day (February 28, 1978) for Case 5 (Table 12). The result was above zero, but less than 0.3. The value in the "Report" column of the logbook is a censored result: "<0.3."

Examination of the logbook "Report" values indicates that negative values were often treated as zero for the purpose of averaging the bioassay sample. Worker 1 in Table 13 illustrates one such case; there is not enough precision in the case of worker 2 to make such a determination. However, in NIOSH's calculations, the negative values are treated "as is." For example, SC&A identified 16 instances where NIOSH averaged negative raw results with positive raw results to gain an overall average value that was *at or above* the MDA of 0.3 dpm/1.5 L. There were 62 additional cases in which negative raw results were averaged with positive raw results (results above the MDA) yielding an overall average value that was *less than* the MDA.

SC&A is also troubled by the large variations in the results from multiple analyses of the same urine samples. NIOSH has described the data logging procedure as follows:

> *The data in the logbooks consisted of one or more corrected activity rate results for each urine sample in units of dpm per disc, depending on how many times a sample was counted, and on count-specific results in units of net dpm/1.5 L.* [NIOSH 2012, p. 19]

We infer from this, that when the data show a number of disc results on a particular day, the values relate to measurements of the same sample. SC&A has verified with NIOSH that this is

the correct interpretation (Taulbee 2013). SC&A finds it remarkable that these values vary a great deal, sometimes by more than an order of magnitude. This is illustrated in a number of cases in Tables 13 through 16; other examples can be found in Tables 8 through 12. It is even more remarkable in Tables 13 and 15, since the below MDA values are negative in those examples.

An investigation into the quality of the analysis of urine samples and the procedures for handling and reporting the data appears to be warranted, given its centrality to worker dose estimation, whether directly from the data as entered into worker records or indirectly in coworker models.

Table 13: Two Examples of Highly Variable Results that include Negative Values as well as Above MDA Values from the Same Urine Sample

	Date	Disc1 dpm/1.5 L	Disc2 dpm/1.5 L	Disc3 dpm/1.5 L	Logbook "Report" Result
Worker 1	12/5/88	-0.08	0.699		0.35
Worker 2	9/26/83	-0.05	0.547	0.483	0.3

Table 14 shows highly variable results that are above zero but with the same samples giving results that are well below and well above the MDA.

Table 14: Examples Showing Averaging of Highly Variable Results Well Below and Well Above MDA

	Date	Disc1 dpm/1.5 L	Disc2 dpm/1.5 L	Disc3 dpm/1.5 L	Disc4 dpm/1.5 L	Logbook "Report" Result
Worker 1	10/3/88	0.621	0.079			0.35
Worker 2	2/21/79	0.165	0.343	0.009	0.724	0.3

SC&A also notes that the practice of averaging negative with positive values does not appear to have been consistently followed. This is illustrated in Table 15, where in one case the negative value was not included in the average (the first row of data), while in the second, it was (though it is unclear whether it was taken at face value or as a zero). The data in Table 15 represent different samples given by the same worker on the same day.

Table 15: Illustration of Inconsistent Practice in the Treatment of Negative Results in OPOS Calculations

(Special samples taken on the same day from the same worker)

	Disc1 dpm/1.5 L	Disc2 dpm/1.5 L	Disc3 dpm/1.5 L	Disc4 dpm/1.5 L	Logbook "Report" Result
9/26/83	2.393	4.956	2.684	-0.032	3.3
9/26/83	-0.05	0.547	0.483		0.3

In addition, the example in Table 15 shows that samples taken on the same day had very different normalized results. The times that the samples were obtained are not known. The reported values differ by more than an order of magnitude. It is difficult to conclude on the validity of those inconsistent results, as we do not know if one sample was taken before exposure

and the other after exposure. Finally, Tables 15 and 16 show further examples of highly variable results from the same urine sample.

Table 16: Three Examples of Highly Variable Results from Re-Analysis of the Same Urine Sample

	Date	Disc1 dpm/1.5 L	Disc2 dpm/1.5 L	Disc3 dpm/1.5 L	Disc4 dpm/1.5 L	Disc5 dpm/1.5 L	Report
Worker 1	4/4/75	0.553	1.021	0.292			0.6
Worker 2	1/12/89	0.048	0.595				0.322
Worker 3	1/2/79	0.14	0.22	0.663	1.786	0.414	0.6

4.2.1 External Dose and Values Below the Limit of Detection

SC&A also notes that the NIOSH external dose reconstruction guidance does not allow the use of values below half the LOD, even when they are so recorded. Specifically, the NIOSH external dose guidance for "Missed Dose" states:

> *The method to be used for dose reconstruction related to EEOICPA is to assign a dose equal to the LOD divided by 2 for each dosimeter measurement that is recorded as zero or if it is below the limit of detection divided by 2. Readings greater than or equal to LOD divided by 2 are to be used as recorded.* [OCAS 2007, p. 16]

Table 2.1 in OCAS 2007 provides examples of how this guidance is to be used for an LOD of 30 mrem. When the recorded value is zero, the dose to be assigned is 15 mrem (LOD/2); the same 15 mrem dose is assigned when the recorded value is 10 mrem. But if the recorded value is 25 mrem, still less than LOD, the value to be used in dose reconstruction is as recorded—25 mrem (OCAS 2007, Table 2.1, p. 16). This is a reasonably claimant-favorable approach. This protocol was introduced as part of a major revision of the external dose reconstruction procedure made in 2006 (OCAS 2007, p. 4).

4.2.2 Notes on Claimant Favorability

NIOSH's method of calculating OPOS by taking all results at face value would be very claimant unfavorable when there are a large number of results below the MDA. In the present instance of americium data, the vast majority of results are not only below the MDA, they are well below MDA/2 and even MDA/3. For the 4 years shown in Table 6, about four-fifths of the values for NCWs and CTWs combined are below one-third the MDA, and almost all values are below the MDA. There are no values over the MDA of 0.3 dpm/1.5 L in 1974 and 1983. There is only one in 1976; there are six in 1978. For this specific dataset, the results for coworker trivalent actinide (Am, Cm, or Cf) or thorium doses estimated in this way would be very claimant unfavorable throughout the 1972–1989 period, i.e., for the entire period under review for which NIOSH proposes to use in-vitro bioassay data.

It should also be noted that whether results below the MDA (or DL) are logged as "<" results or simply reported as calculated has been a matter of convention at SRS. The reporting convention

does not change the physical reality of what can be detected and the accuracy (or error) of the detection. This is recognized by the 2001 SRS Internal Dosimetry TBD. In fact, it notes that the practice at SRS has changed:

> *The term "less-than data" refers to data that are reported as less than some reporting or decision level. For example, plutonium urine bioassay can be reported as <0.1 d/m/L* [disintegrations per minute per liter] *and a Ce-144 whole body count as <20 nCi.* ***In the past decade, the transition has been made to reporting all actual bioassay results*** *(whether above or below the decision level) with analytical errors. Thus, the issue of less-than results is of interest only for the evaluation of historic intakes.*
>
> *Less-than data are used as a constraint on a fit; the predictions of a model should agree with the less-than data. For example, if a model predicts a urine concentration of 0.002 d/m/L and the measured concentration is <0.1 d/m/L, the empirical and expectation results are in agreement. Less-than data are not used for residual plots, the Runs Test, or least squares fitting procedures; however, most codes in use at SRS accept less-than data and plot it along with positive measurements to allow easy comparison.* [Internal Dosimetry 2001, p. 6-19] [Emphasis added]

SC&A's examination of the data revealed that the practice for americium went from stating the calculated value as "<" when it was less than the MDA prior to mid-1971 to entering the calculated value when the measurement was normalized to a volume of 1.5 L. However, in all such cases, a "<0.3" was entered in a column titled "Report" when the calculated average result was less than the MDA.[9] Given the statement quoted above in the SRS 2001 Internal Dosimetry TBD, and the fact that no analytical errors were reported, it would appear that the intent was that the "<0.3" value should be reported and used. Furthermore, in line with the passage quoted above, data from the 1990s and the 2000s have an explicit column titled "Error" that is not present in earlier data.[10]

SC&A's review of the reporting practices in the raw data, NIOSH dose reconstruction methods heretofore, and the 2001 SRS Internal Dosimetry TBD leads to the conclusion that NIOSH's use of the calculated value in OPOS results, rather than the value in the "Report" column, has an element of arbitrariness in it when the result is below the MDA. It is a choice that is not based on any scientific criterion that SC&A has found; moreover, it is not claimant favorable. In the present instance of trivalent actinide data, NIOSH's choice is systematically very claimant unfavorable.

[9] The raw data can be found on a spreadsheet titled, "Am Final Complied_SRS_WHC_06302011r2_Ready Updated rev2.xlsx' on the "O Drive" in the folder "Savannah River Site SEC/SRS Databases for Coworker Models 02172013."

[10] Data from the 1990s and 2000s can be found on a spreadsheet entitled, "SRS HPRED data by nuclide OPOS method R4.xlsx' on the "O Drive" in the folder "Savannah River Site SEC/SRS Databases for Coworker Models 02172013."

A scientifically defensible and clearly claimant-favorable approach would be to use 0.3 dpm/1.5 L as the censoring level for OPOS calculations relating to trivalent actinide data for the 1972–1989 period. This choice is also compatible with the raw data where the "Report" column lists below MDA values as "<0.3," as well as with individual worker files where the "Report' column value was entered by SRS personnel.

Finally, a clear and defensible censoring level is needed for CTW vs. NCW comparisons to be statistically meaningful. The current NIOSH approach contains varying levels of below and above MDA results. Furthermore, the CTW and NCW bioassay monitoring practices were not comparable, as discussed in Section 3.1. The resulting conclusion that CTW and NCW data are from the same distribution based on the combination of these problems must be regarded as essentially statistically meaningless. As one specific illustration of the problem, the NIOSH data do not even allow for an estimation of the minimum number of samples required for a valid CTW-NCW comparison because a clear censoring level is not defined. In addition, as noted in Section 4.2, the uncertainties in many of the results used to calculate OPOS are very high, as exemplified by the fact that multiple results of analyzing the same urine sample often give results that differ by an order of magnitude or more. Such variations do not allow for detection of tendencies in urine sample results in a given time period.

4.2.3 Bioassay Samples After Chelation

NIOSH's procedure for calculating OPOS sample values has certain exclusions. Specifically, the SRS worker model document specified that samples "marked "DTPA" to indicate chelation" were among the ones that were excluded from the calculations (ORAUT 2013, p. 16). However, SC&A found that the trivalent actinide OPOS values uniformly included *all* of the post-chelation samples that we checked involving more than three dozen workers. The samples covered essentially the entire time-span for which NIOSH proposes to use bioassay data for the thorium and trivalent actinide coworker model. The details of the samples are shown in Attachment E.[11]

The administration of DTPA, given to decorporate incidental intakes of certain radionuclides, like Am-241, Cm-244 or Pu-239, enhances their excretion. The use of results from such samples to calculate thorium intake rates is not scientifically acceptable, even if it is claimant favorable. SC&A presumes that this was the reason that NIOSH decided to exclude DTPA-related urine samples. The practice, however, contradicts the stated policy.

In addition, the use of such data contradicts ORAUT-OTIB-0081, Rev.1 (ORAUT 2013), which states that samples marked DTPA indicate chelation were excluded.

Finding 13: NIOSH's interpretation of below minimum detectable activity (MDA) results for OPOS calculations is an interpretation of data entry conventions that contains an element of arbitrariness. It is systematically claimant unfavorable when a large fraction of the results are well below the MDA. This finding applies to all cases where NIOSH proposes to use OPOS data as presently calculated for coworker models, including those whose data are reviewed in this report (Am, Cm, Cf and thorium) as well as others, such as neptunium and fission products.

[11] The names of the workers have been deleted to protect privacy.

Finding 14: NIOSH's approach to using data well below the MDA, including negative numbers and zeros to calculate OPOS values, can sometimes yield scientifically meaningless results such as negative OPOS values, implying negative intakes. The problem of negative OPOS results is especially prevalent in the 1983–1989 period.

Finding 15: The present NIOSH method of calculating OPOS data would result in systematically very claimant-unfavorable results in the case of the Am, Cm, Cf dataset. This would be true of thorium dose estimates as well as Am, Cm, Cf dose estimates. This is because the vast majority of bioassay results for the 1972–1989 period are well below the MDA.

Finding 16: SC&A is concerned that some reported results in the logbooks that are above the MDA are averages of results that are both well below and well above the MDA. This is much better than the NIOSH OPOS procedure when even below MDA results are used at face value, but it is still a concern since such practices vitiate the connection between the raw data and the workers' intake experience in the real world.

Finding 17: NIOSH's coworker data compilation procedure states that chelation-related bioassay samples were excluded from OPOS calculations. However, SC&A found that, contrary to this procedure, chelation-related samples were included in the OPOS averages in every case.

Finding 18: SC&A's examination of the raw data with reported results above the detection limit shows that sometimes the same urine sample, counted in different discs, presents inconsistent results. This indicates that the method used for detection of activity was not always reliable; such widely inconsistent results from the same urine sample cannot be trusted.

Finding 19: Many reported OPOS values that are above the detection limit are actually the average of negative and positive normalized disc results, or are the average of results with large differences among the different discs derived from the same urine sample. Such average results no longer retain an unambiguous connection to the intake of the worker, do not represent excretion rates of workers, and therefore should not be used to calculate intake rates.

Finding 20: Many reported OPOS results below the detection limit are the average of normalized disc results that have a large variation between them. This indicates that the resultant average of disc results is highly uncertain. Such average results do not have an unambiguous connection to the intake of workers, do not represent excretion rates, and should not be used to calculate intake rates.

4.3 DATA ADEQUACY BY JOB TYPE FOR CONSTRUCTION TRADES WORKERS

The trivalent actinide database was queried for the specific job titles of "pipefitter" and "laborer;" only 4 workers were identified as pipefitters and 14 were identified as laborers. We looked at these two job titles because in prior analyses, SC&A had found that they may have had higher exposure potential in some periods for tritium (SC&A 2010a and SC&A 2010b).[12] These numbers are insufficient for a comparison of the exposure potential of these CTW job types with CTWs as a whole (or with NCWs).

While a statistically valid comparison is not possible with the data available, it is still instructive to look at the results for these two groups, shown in Tables 17 and 18. Table 17 shows that two of the four pipefitters had positive OPOS results[13] from samples covering September through December of 1984. No additional information is available in the database to describe the specific duties of these two workers. Table 18 shows that 3 of the 14 identified laborers had positive OPOS results; 2 of these workers had positive results in 1973 and the third worker had a positive result in 1986. These numbers indicate higher fractions of above MDA results than is typical of the fractions for CTWs as a whole shown in Table 3. More strongly, they indicate the serious inadequacy of the data available to compare the exposure potential of CTW subgroups.

Tables 17 and 18 also show the total number of individual bioassay samples, the total number of these samples that were above the MDA (designated as "positive" results), and the period in which the samples were taken. In the case of the pipefitters, about half of the total samples were taken in the September–December 1984 time period at frequencies that indicate sampling associated with an incident. The pattern is less clear with the data for the laborer job type. As before, the term "positive" is used here to mean an OPOS result equal to or more than the MDA of 0.3 dpm/1.5 L.

Table 17. Overview of Available Pipefitter OPOS Data

Pipefitter #	# Results	# Positive Individual Results	# OPOS Results	# Positive OPOS Results	Time Period
1	16	9	1	1	Sep-Dec 1984
2	17	10	1	1	Sep-Dec 1984
3	1	0	1	0	Jan 1984
4	3	0	1	0	Nov 1973

[12] SC&A has not done a job-type analysis for other radionuclides, though it has compared exposure potential of CTWs in particular work areas compared to CTWs as a whole and compared to NCWs as a whole (SC&A 2010a). SC&A has long raised this as a broader issue for the SRS SEC but had not yet received an analysis or response from NIOSH as of the February 12, 2013 Work Group teleconference meeting. , NIOSH stated that they would discuss it internally after the Work Group call (ABRWH 2013, p. 50 and p. 65). There has been no further analysis on the topic from NIOSH since that time.

[13] The term "positive" result is used in the sense of above the MDA, as per the convention noted in ORAUT 2007, p. 12.

Table 18. Overview of Available Laborer OPOS Data

Laborer #	# Results	# Positive Individual Results	# OPOS Results	# Positive OPOS Results	Time Period
1	10	0	6	0	1973–1978
2	3	0	2	0	1973, 1977
3	11	7	1	1	1973
4	1	0	1	0	1979
5	1	0	1	0	1979
6	1	0	1	0	1979
7	2	0	1	0	1979
8	1	0	1	0	1979
9	13	6	2	1	1986, 1987
10	1	0	1	0	1979
11	1	0	1	0	1979
12	11	6	2	1	1973, 1979
13	7	0	1	0	1973
14	2	0	1	0	1976

Finding 21: The number of data points for CTW job types is inadequate to compare relative thorium exposure potential for CTW job types for the 1972–1989 period or to compare the exposure potential of specific CTW job types with NCWs.

5.0 EVALUATING THE INTERPRETATION OF TRIVALENT ACTINIDE RESULTS AS THORIUM

There are no thorium-specific bioassay data in the period under review. NIOSH's approach of using Am/Cm/Cf data raises two questions:

- Was thorium extracted along with Am/Cm/Cf in the urinalysis method being used at SRS during the period in question (1972–1989), and if it was, what was the efficiency of extraction?
- Would an interpretation of an Am/Cm/Cf bioassay result as thorium be scientifically reasonable for all relevant organ doses and solubilities?

We review each of these questions in turn.

5.1 THORIUM EXTRACTION EFFICIENCY

NIOSH's scientific basis for interpreting Am/Cm/Cf bioassay data as thorium when the worker situation indicated thorium exposure potential depends on its conclusion that thorium would be preferentially extracted along with Am/Cm/Cf in the method in use at SRS during the 1972–1989 period. SC&A raised the question of the efficiency of the relative extraction of thorium relative to the other radionuclides (see Attachments A and B). NIOSH published a review of this topic and concluded that thorium was extracted into the Am/Cm/Cf stream with about 97% efficiency (Glover, Neton, and Taulbee 2013). SC&A reviewed this paper as part of its review of the thorium dose reconstruction issue. This review is presented in Attachment D.

The result of the review is that SC&A agrees with NIOSH's conclusion that the thorium extracted along with Am/Cm/Cf in the SRS laboratory bioassay procedure is scientifically reasonable and well-supported.

5.2 INTERPRETATION OF AMERICIUM RESULTS AS THORIUM

NIOSH has proposed to interpret Am/Cm/Cf data as thorium or as one of the three trivalent radionuclides, depending on which estimated dose result is the most claimant favorable. While this would by definition be friendly to claimants, the method must also meet the tests of scientific reasonableness. SC&A has some concerns in this regard.

5.2.1 Radionuclide Exposure Relative to Radionuclide Monitored

Work with the three trivalent radionuclides was quite different from work with thorium, even though there was some overlap in the places where such work took place. For instance, the production and separations processes for the trivalent radionuclides took place in a series of irradiation and separation steps (SRS 2000, Figure 1, p. 158). These processes had nothing to do with thorium, whose targets were also irradiated (though not in the 1972–2007 period under consideration). Interpreting Am/Cm/Cf bioassay results therefore requires knowledge of whether the sampling done in the particular time and location under consideration involved trivalent actinide work or thorium work or both. If it was one or the other, it is possible to

interpret the results consistently and reasonably, but one must know which radionuclide it is, especially since thorium work was generally separate and different from Am/Cm/Cf work (even if much of it occurred in the same general areas of SRS, such as 773-A or the 200 Area). For instance, thorium-232 was often used as a surrogate for plutonium-238 or plutonium-239 not only because of its similar chemical properties, but also because of its very low specific activity (in contrast to Am-241, Cm-224 and Cf-252). As we will see in Section 5.2.2, incorrect interpretation of the data in regard to the radionuclide could result in very incorrect results in at least some cases (either unjustifiably claimant favorable or very claimant unfavorable).

The problem is even more technically challenging if there was exposure to both the trivalent actinides and to thorium in the same period. Consider, for instance, a situation where an employee worked for 8 months in a job where he was exposed to americium, but not to thorium. Now suppose he was then assigned for the next 4 months to work that had thorium exposure potential. If the worker was monitored while doing both these jobs, the OPOS value would be calculated using exposures to two different radionuclides, mixing oranges with apples. Furthermore, the solubilities may also have been different, making a reasonable interpretation of the result even more remote.

The above leads us to conclude that the OPOS approach that would interpret Am/Cm/Cf as any one of those three or as thorium requires certain minimum conditions to be met before a reasonable technical interpretation could be given to it.

A further complication is that NIOSH is basing its coworker model on a conclusion that CTW and NCW measurement distributions were the same. However, it has not provided evidence that CTWs and NCWs were exposed to the same mix of radionuclides. Hence, the bioassay data for NCWs and CTWs may or may not represent comparable intake conditions.

Finding 22: Trivalent actinide OPOS results can only be applied in a scientifically defensible way if there is knowledge of whether the worker was exposed to one of the trivalent radionuclides or to thorium. Intake results would not be scientifically credible in the absence of this information.

Finding 23: NIOSH has not provided evidence that there are data to differentiate between thorium and trivalent actinide exposure. In the absence of such information, it is not possible to establish whether the bioassay data for NCWs and CTWs represent comparable intake conditions.

5.2.2 Comparing an Americium Interpretation of a Bioassay Result with a Thorium Interpretation

SC&A did some example calculations in order to check that NIOSH's method of interpreting trivalent actinide data as thorium would give scientifically reasonable results in all relevant cases. Specifically, SC&A compared the Am-241 lung and bone doses for a worker who might have had exposures in 773-A, where both thorium and Am/Cm/Cf were handled, to the thorium lung and bone doses. It was assumed in the first case that the worker was exposed only to thorium (232 and 228) and Ra-228 in equal activity amounts and in the second case that he was

exposed only to Am-241. The worker's excretion rates were the ones described in the coworker model assumed by NIOSH to be the same, as described in Table 7-6 in SEC-00103 ER, Addendum 3, and in the associated text (NIOSH 2012, Table 7-6, p. 29).

In the first case, the excretion rate data were interpreted as a constant intake of thorium over the 1973–1994 period. NIOSH has calculated 34-year committed doses to lung and bone, due to intakes of equal activities of Th-232, Th-228 and Ra-228, for both Type M and Type S thorium. For comparison, SC&A assumed that the worker was exposed only to Am-241, Type M. NIOSH has calculated the coworker's daily intake rates of Am-241 as 0.826 dpm/d from 1973 to 1994 in NIOSH's SRS coworker model report (ORAUT 2013, Table 5-7, p. 27). Using this NIOSH-calculated intake rate for Am-241, the committed 34-year doses (i.e., to 2007) for intakes during 1973–1994, SC&A estimated 0.25 rem to the lung and 7 rem to bone. The results are shown in Table 19.

Table 19. Comparison of 34-year Committed Doses for Thorium and Americium using the Same Excretion Rates

Material Type	Lung Dose (rem)	Bone Dose (rem)
Type M thorium	2.6	18.66
Type S thorium	79.92	23.34
Type M americium	0.25	7

Notes: Type M and Type S thorium results are reproduced from Table 7-7 of NIOSH 2012 (p. 30). Type M americium results were calculated by SC&A using input data in NIOSH 2012, Table 7-6 (p. 29). We note that on p. 29, NIOSH describes the Type M bone dose as 19.09 rem and the Type S lung dose as 72.18 rem. These are slightly different from the dose values shown in Table 7-7, page 30, of the same document. We have used the values in Table 7-7.

Table 19 shows that when the bioassay data are interpreted in a claimant-favorable way in terms of thorium solubility, the claimant-favorable lung dose for thorium is over 300 times greater than the americium dose. The discrepancy is not as great for bone dose, but it is still more than a factor of 3.

This comparison shows that it is critical to accurately know whether a worker was working with thorium or americium in interpreting trivalent actinide urinalysis results in the fairly common case of lung or bone dose estimation. If the information about the specific radionuclide to which the worker was exposed is not accurate, the resulting lung dose and bone dose estimates could be very inaccurate.

Bioassay data contain notations about the area of work, e.g., 773-A. However, the records that SC&A has reviewed for the period up to 1989 do not indicate whether a worker who was monitored for the trivalent radionuclides, Am/Cm/Cf, worked with thorium.

Finding 24: Lung doses for trivalent radionuclides, which NIOSH always interprets as Type M, would be far lower than the lung dose when the same bioassay data are interpreted as Type S thorium. Scientifically reasonable dose estimates therefore require knowledge of the time and place of exposure potential to thorium for workers with Am/Cm/Cf bioassay data. NIOSH has

not shown that it has the necessary information to interpret the bioassay results as thorium instead of the specific trivalent radionuclide(s) noted in the bioassay record.

Finding 25: Incorrectly assigning a trivalent radionuclide dose conversion factor to a worker exposed to Type S thorium would yield a very claimant-unfavorable lung and bone dose estimate.

Finding 26: Incorrectly assigning a Type S thorium lung dose to a worker exposed to Type M Am, Cm, or Cf would result in a very large and scientifically unwarranted overestimate of the dose. Assigning all intakes to thorium when the exposure was actually to a mixture of the various radionuclides would also overestimate the lung and bone dose.

6.0 THE 1990–2007 PERIOD

6.1 MONITORING METHODS

NIOSH has stated that "SRS identified chest counting as the monitoring method of choice for thorium in the 1990 and 2000 versions of the internal dosimetry technical basis documents (Internal Dosimetry, 1990; Internal Dosimetry, 2001)." (NIOSH 2012, p. 19).

The 1990 SRS Internal Dosimetry TBD cited by NIOSH provides the following description of the thorium monitoring program:

> *The worker monitoring program for thorium shall consist of*
> - *annual urine bioassay*
> - *annual chest count*
> - *semi-annual fecal bioassay*
> - *personal air sampler (PAS)*
>
> *If respiratory protection is not used Health Protection Operations may use either fecal bioassay or PAS or both. If respiratory protection is used then fecal bioassay is required and PAS is optional.* [Internal Dosimetry 1990, Chapter 10, p. 8]

SC&A was unable to locate a statement in the 1990 SRS Internal Dosimetry TBD that stated that chest counting was the method of choice for thorium monitoring. On the contrary, the following general direction is provided for evaluating intakes of radioactive material:

> *Bioassay is the preferred method to assess intakes, but breathing zone air sampling data may be used in situations where adequate bioassay data are not available.* [Internal Dosimetry 1990, Chapter 2, p. 5]

The context of the report makes clear that "bioassay" refers to urine or fecal bioassay rather than in-vivo counts. The missed 12-month effective dose equivalent for an annual chest count for Class W thorium-232 is listed as 250,000 millirem and for Class Y is listed as 3,100 millirem (Internal Dosimetry 1990, Chapter 10, p. 8). These are far higher than the 100 millirem threshold for initiating monitoring. Moreover, organ doses for the intakes corresponding to these effective dose equivalents would be far higher for certain organs, such as the bone surface (Types M and S) or the lung (Type S).

NIOSH believes that "those who were exposed were monitored" (Makhijani 2013a) in this period. But the above chest count capabilities indicate that even if workers were monitored, the equipment was not capable of meeting the 100-mrem criterion for thorium.

The 2001 version of the same SRS TBD states that thorium is monitored by chest counts and that thorium bioassay was not done (Internal Dosimetry 2001, pp. 5-11 and 5-12). According to this TBD, a state-of-the-art in-vivo facility was set up in 1995 (Internal Dosimetry 2001, Chapter 11). We note here that Addendum 3 of the ER would have started the use of in-vivo data for thorium

intake assessment in 1995 (NIOSH 2012, pp. 28-30). However, during a technical call in January 2013, NIOSH stated that it was going to use in-vivo data from 1990 onward (Attachments A and B). This leaves open the question of what in-vivo facility was used between 1990 and the end of 1994. Presuming it is the facility that is specified in the thorium section of the 1990 Internal Dosimetry TBD, the minimum detectable doses are far above the 100-millirem limit required for initiating monitoring.

The 2001 Internal Dosimetry TBD provides a chest-counting MDA for thorium-228 of 0.15 nCi if Pb-212 is counted and if it is in equilibrium with Th-228. The MDA for Th-228 based on 84.4 keV photons is listed as 3.2 nCi (Internal Dosimetry 2001, p. 5-11). The MDA for 59 keV Th-232 photon is listed as 31 nCi (Internal Dosimetry 2001, p. 5-12). SC&A notes that it is generally impractical, if not impossible, to measure Th-232 photons directly using WBC because of low photon yields. Furthermore, the 31 nCi MDA is high and impractical. SC&A also is skeptical about the use of the 84.4 keV thorium-228 photon. Normally, Th-232 and Th-228 are measured in-vivo through their daughters Ac-228 and Pb-212.

SC&A notes that while the in-vivo counting facility with the Pb-212 MDA of 0.15 nCi became operational in 1995, according to the 2001 Internal Dosimetry TBD (Internal Dosimetry 2001, pp. 11-1 and 11-2), NIOSH states that it was placed into operation in 1989 (NIOSH 2012, p. 19). NIOSH's reported MDA of 0.15 nCi for Pb-212 at this facility (Attachments A and B) is the same as that reported in the 2001 Internal Dosimetry TBD, where the operational date is given as 1995.

In addition, SC&A's review of worker data indicates that most scans at this time used a FASTSCAN facility. While this was common in the 1980s, a new machine was part of the new in-vivo arrangements that were installed in 1995 (Internal Dosimetry 2001, Chapter 11). The 2001 SRS Internal Dosimetry technical basis document notes the following limitations of FASTSCAN counting:

> *The NaI detectors measure photons in the energy range of 80 keV to 2000 keV. Data below ~200 keV is difficult to interpret due to the Compton backscatter peak. However, with sufficient activity, for instance in the case of medical administration of radionuclides, or with a calibration source, quantification of activity in this energy range is possible. The system is efficiency calibrated from 661 keV to 1460 keV for routine operations using a Department of Energy (Pacific Northwest National Laboratory) Bottle Manikin Absorption (BOMAB) Calibration Phantom.* [Internal Dosimetry 2001, p. 11-5]

The above limitations would make FASTSCAN data unusable for the 86.5 keV Th-228 photon except at extremely high levels of intake comparable to medical administration. The range of system efficiency calibration would also make FASTSCAN results marginal at best for the 238.6 keV photon of Pb-212. This Pb-212 photon is normally measured with lung counters or directly via head or knee counting. Even a meter arc geometry gives detection limits too high to be practical.

The discussion of source terms in Section 2 shows that significant quantities of thorium-232 may have been processed up to and including 2003 and beyond, including for use as a surrogate radionuclide. The absence of positive results identified so far for thorium-related photons for any of the in-vivo counting data may indicate very low exposure potential. On the other hand, it may indicate sparse WBC monitoring of the workers who had exposure potential. Since NIOSH has not compiled the in-vivo data for the 1990–2007 period, along with detection limits, it is not possible for SC&A to determine whether (1) there was low thorium exposure potential for essentially all workers, or (2) there was significant exposure potential for some workers, though they may have been a small fraction of the total number of workers. SC&A notes that there was use of thorium for various activities in the 1990–2007 period (see Section 2).

Finding 27: The MDAs for thorium by chest counting in the 1990 Internal Dosimetry document are far higher than the 100 millirem level required to initiate routine monitoring.

Finding 28: Due to conflicts between statements in the NIOSH ER and in the SRS 2001 Internal Dosimetry technical basis document (TBD), it is not possible for SC&A to definitively establish the date when the MDAs for chest counting described in SRS 2001 became operational. This problem would apply specifically to the 1990–1994 period.

Finding 29: NIOSH has not compiled in-vivo counting data for the 1990–2007 period (including detection limits) that would be relevant to thorium intakes. Therefore, it is not possible for SC&A to evaluate whether thorium exposure potential was low or whether at least some fraction of workers, possibly small, had significant thorium exposure potential. It is also not possible to evaluate whether the quantity and quality of data are adequate for thorium dose estimation in the 1990–2007 period.

Finding 30: The FASTSCAN specifications indicate that the detection limit for thorium would be so high as to render it practically undetectable in SRS workplace situations.

6.2 THORON

NIOSH has stated that the detectors were sophisticated enough to have an MDA of 0.15 nCi for Pb-212 (Attachment A). However, thorium was stored in various areas of the site, including the areas where it was processed. This fact, as well as site documentation, indicates the presence of thoron, and Pb-212 is a daughter product of thoron. Even if there were Pb-212 measurements identified in whole-body (or lung) counts, a clear definition of the thoron source term would be needed to interpret them. This problem is especially acute because the site itself did not identify thorium-related peaks:

> *Th-232 is assumed to be the principal source of thorium intakes. NIOSH has not identified claimant results of in vivo analyses performed for thorium. However, the chest counter was calibrated to detect photons from the Th-232 progeny, including Th-228 and Pb-212. The chest counter, placed in operation in 1989, was configured with an array of four low-energy germanium detectors with thin carbide windows capable of measuring 15 to 400 keV photons (Internal Dosimetry, 2001). That energy range spans the energies of interest for the*

> *Th-232 and its progeny. The 84.4 keV gamma energy line of Th-228 and the 238.6 keV energy line of Pb-212 were not normally listed in the SRS chest-counter software analysis library. However, if statistically significant activity was present in the individual worker examinations, then photo peaks of those energies would have been listed on the chest count report as* ***unidentified****. These* ***unidentified*** *peaks would have been resolved and identified as thorium during the report review process. Depending on the skill of the SRS HP analyst, the possibility exists that the association of the unidentified peaks with Th-232 may have been missed. However, unresolved* ***unidentified*** *peaks would be listed on the in vivo count reports available to the NIOSH dose reconstructor for resolution when reviewing the individual's dose records.* [NIOSH 2012, pp. 19-20][14]

This was reaffirmed by NIOSH during the January 2013 technical call (Attachment A).

Neither NIOSH nor SC&A have found data that would indicate that thorium was actually measured or that Pb-212 was detected in chest counts. Furthermore, there are no other indications in the data that would identify thorium as the source of the counts. Using Pb-212 photons to infer thorium-232 body burdens requires knowledge of the thoron source term. It is difficult to see how NIOSH could reliably use Pb-212 data in the absence of any positive count. The problem would even be complex with some positive Pb-212 counts because the biokinetics of Pb-212 are different than those of thorium-232. Specifically, the daughter products leave the lungs at a faster rate than Th-232.

As discussed in Section 6.1, the lack of positive counts may indicate a lack of exposure potential. But it may also indicate a lack of attention to thorium exposure potential. Since NIOSH has not compiled the relevant data, it is not possible at present to know (1) whether there was exposure potential, and if so to quantify it, and (3) whether there are adequate data to adjust for the disequilibria created by thorium processing.

Finding 31: NIOSH has not provided information on how it will distinguish between Pb-212 results due to thoron from those resulting for thorium-232 intakes.

Finding 32: In the absence of a compilation of whole-body count (WBC) and chest count data, it is difficult to see how NIOSH will assign thorium doses to workers or construct a coworker model for the 1990–2007 period. There were thorium-related activities at SRS during this period.

[14] The word "unidentified" in bold in this quote was in italics in the original.

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ATTACHMENT A: JANUARY 23, 2013, CONFERENCE CALL NOTES

Notes of the technical call on January 23, 2013, on SRS SEC-00103. Based on questions sent to NIOSH in the memorandum of January 4, 2013 to Tim Taulbee from John Stiver and Arjun Makhijani.

Final, with participant corrections incorporated.

The call was from about 11 am to about 12:30 pm, Eastern Standard Time, January 23, 2013.

These notes are NOT verbatim though presented in the form of the flow of the conversation during the call. The questions in each section were sent to NIOSH on January 4, 2013. The notes following each question were taken during the call. Separately from these notes, NIOSH also provided written responses to the questions to SC&A and the Work Group.

Present: Mark Griffon, Brad Clawson, Phil Schofield, Jim Lockey, Ted Katz, Tim Taulbee, Jim Neton, Liz Brackett, Matt Arno, Mike Mahathy, Don Bihl, John Stiver, Harry Chmelynski, Joyce Lipsztein, Arjun Makhijani.

Ted: I want to remind everyone this is not a Work Group that should entail a back and forth. It is only for clarification of existing documents.

Mark Griffon: I agree with Ted regarding the purpose of the call. It is basically for SC&A to get clarifications from NIOSH on various documents.

A. Neptunium dose estimation as specified in ORAUT-RPRT-0056 [ORAUT 2012c], dated August 20, 2012

1. The neptunium dose reconstruction method proposed by NIOSH in ORAUT-RPRT-0056 proposes to use chest count data for certain radionuclides as suitable stand-ins (or surrogates) for neptunium-237, based on overlap of spectral lines. We did not find any information on how NIOSH plans to establish that the workers who were monitored for the surrogate radionuclides that were measured also had exposure potential to neptunium at the relevant times and places. Has NIOSH developed such information to show that the surrogate radionuclide data are indeed relevant for neptunium exposure potential at the appropriate times and places? If so, could NIOSH make the data available to SC&A?

Tim: There are two parts to this question. One is: who were the people exposed to neptiunium-237 during the post-1972 period? Workers who had neptunium exposure potential were in the 200 Area, 773 Area and the 300 Area (where they did target fabrication). Workers received Whole Body Counts [WBC]. Unmonitored workers had lower potential for exposure. There seems to be a misunderstanding about how WBC data are to be used in the proposed dose reconstruction method. We are not going to use surrogate radionuclides. SRS identified [spectral] regions of interest and the neptunium energies are similar to those of I-131 and Cr-51. So it isn't that these radionuclides [I-131 or Cr-51] were present; it is that region of interest is

shown in the WBC and we can look at MDA for neptunium based on that. Whole body counts were done on virtually all workers.

Arjun: Np-237 is called out explicitly in some whole body counts; the spectral region identified for it was between 230 and 290 keV. But it is not called out in others. Why?
Tim: Are you sure it was not Np-239?

Arjun and Joyce: It was Np-237.

Joyce: Did everyone get a whole body count?

Tim: Yes.

Arjun: Were all workers counted every year?

Tim: No. But some workers especially in the 200 Area (F and H) were monitored by bioassay every year per SRDB 11266.

Joyce: If they were targeting people with I and Cr exposure potential for monitoring in a particular year, wouldn't they miss the workers who were working with Np?

Tim: Not necessarily. People most likely getting WBC were in the 200 Area, which is where neptunium separation was going on.

Joyce: But if they were targeting I-131, the position of the detector would be different than if they were measuring a broad range of radionuclides.

Tim: No they were not just targeting I-131. They were targeting a whole bunch of gamma emitters – iodine-131, Cs-137, Ce-144, Co-60, K-40, Cr-51.

Joyce: There is the issue of distribution of Np in the body – it stays in the lung for a longer time than other radionuclides, so calibration will be different if you are looking for neptunium.

Tim: That is why WBC would pick up Np, even if done once a year.

Joyce: I am asking whether there is some other kind of efficiency calculation. Various types of whole body counters were used for in vivo monitoring. In order to calculate the efficiency of those detectors for the Np-Pa distribution in the body it might be necessary to do a Monte Carlo simulation of the detectors geometry. [Post call Joyce note: As discussed below under question 2, there were other in vivo monitoring that did not use the arc geometry like the shadow shield and the stand up counter (Fast Scan.)]

Jim Neton: Not sure why we want to do a Monte Carlo. The modified meter arc geometries used are oriented to being position insensitive.

Joyce: But you are using efficiency of cesium to calculate efficiency of Np.

Tim: No. They developed a multi-nuclide efficiency. Because there was no calibration for Np-237 in the region of interest (ROI), as explained later in the notes, comparison to calibration of another radionuclide was necessary, with appropriate adjustments for photon abundance. Comparison to the Cs-137 calibration was used for two of the reporting formats covering the years 1970 to 1978. Comparison to Cr-51 was used for the third reporting format covering the years 1979–1989.

Joyce: But you should look at it again. Neptunium itself is not counted. Rather it is the daughter product [Pa-233] that is counted. It takes some time for neptunium-237 to be in equilibrium with Pa-233.

Tim: It happens in a matter of months. The MDA can be adjusted for Pa-233 in-growth.

Joyce: So that would make a difference – when the counting is done.

Arjun: Do you have to know the age of the neptunium to apply your model?

Liz: I don't think we do.

Matt: It takes about eight months for Np to reach equilibrium with Pa-233. Whole body counts are once a year. So you have a delay both before and after an intake for Pa-233 to build in. We are targeting annual counts. One should keep in mind that calling out neptunium explicitly was done only for a particular period in the older WBC counts. Then it was not called out as a specific region of interest. Sodium iodide had broader ROIs [than germanium], only about 8.

Arjun: Is that documented somewhere?

Matt: I believe so. There is documentation in OTIB-81. Don Bihl has written a paper.

Arjun: Is OTIB-81 available and if so can you send to SC&A?

Tim: It is undergoing internal review. I hope it will be available within the next month.

Don Bihl will send the paper to Tim and he can send it to others. [Post call clarification: There is not a paper separate from OTIB-81 which will be distributed when approved by DCAS.]

Matt: NIOSH is assuming that Np-237 is in equilibrium with Pa-233. For further information: Pa-233, with a 27 day half-life, reaches equilibrium with Np-237 in approximately 9 months (10 half-lives) and is assumed to be in equilibrium with Np-237 for the basis of calculating chronic intakes with a minimum duration of one year.

Don: When neptunium was explicitly called out, the Np region of interest was lousy; the yields for Np photons were extremely low in this region, just one percent. The best regions to use are ones that overlap with Cr-51 and I-131. The pure Np region was worthless. When we looked at that we decided to use the other regions of interest; we did not care if there was interference from Cr-51 and I-131. If you were running a whole body counting program in the field, you do care if

there is overlap. [The following material was added after the call for clarification about what ORAUT did: On the original whole body counts form, associated with the 40-cm arc detector, and used 1960–1974, there was an ROI labeled Np-237 at 230–290 keV. From an in vivo counting perspective use of this region didn't seem appropriate to us. Np-237 has gammas with-only <0.5% abundance and they are not in the 230–290 keV region. Pa-233 has a 272 keV line but only 0.3% abundance. The best ROI to use is the 300–400 keV with several lines from Pa-233 with reasonable abundance. It is possible, but documentation has not been found, that SRS was worried about interference from I-131 and Cr-51 and did not want to assign counts from the latter radionuclides to Np-237. It is theoretically possible to calibrate the whole body detector for measuring a radionuclide in an ROI just below the principal ROI based on scatter of some gammas from their total energy to the lesser energy. This is not optimal but possible and it appears that is what SRS did for the 40-cm arc detector. The MDA was not good however. SRS did not label a specific energy region of interest for Np-237 from 1975 on so the best region was chosen, which differed slightly depending on the reporting format (300–400 keV for one format and 290–349 keV for another). Because for the EEOICPA it is claimant favorable to assign all of the counts in the preferred 300–400-keV or 290–349-keV ROI to Np-237 even if some were from I-131 or Cr-51, use of the higher energy ROI for Np-237 made better sense than use of the 230–290 keV region. This approach was used in the coworker analysis for 1970 to 1989. Urine data were used in the coworker analysis for years prior to 1970 and for after 1990. Use of chest count data was investigated but the site did not report results in the energy range applicable to Np-237 for the years of interest so chest count data could not be used.

An operational HP would have knowledge of radionuclides of interest as well as what *hazards might* be present in a particular area when there was a potential for different radionuclides in the same region of interest. They'd need an accurate accounting of intakes and dose, as well as interest in what hazards might be present in a particular area. For the coworker study we are assuming the ROI represents Np-237 which is claimant favorable.

Arjun: Why did they not call out Np?

Don: I can't say.

2. Timeliness of monitoring is particularly important in the case of the surrogate radionuclides proposed for neptunium, since I-131 and Cr-51 are relatively short-lived having half-lives of 8 and 28 days (rounded), respectively. Has NIOSH compiled validation data regarding the times of chest counting compared to the periods of Np-237 exposure potential to ensure that the data are relevant for estimating Np-237 intake? If so, could NIOSH provide the validation data to SC&A?

Responses: These are routine WBCs. They do not follow a particular intake. If a worker had had a neptunium intake, it would show up in that region of interest. All of the radionuclides are recorded. Most of the time they did not suspect any intakes.

John Stiver: It sounds like they were doing a broad-based look for gamma emitters.

Joyce: Which geometry are you using? If you look at two model counters: shadow shield geometry and a fast scan. Are you using all those counters? Which ones are you using?

Tim: It varied over time. They switched to flat-bed and then in 1980s they did fast scan.

A: Would your MDA change over time?

Tim: Yes. And efficiency as well.

Joyce: Do you still think with a fast scan you can detect Np?

Tim: I'll get back to you on that.

Arjun: Did they do only fast scans in the 1980s?

Tim: That's a hard question to answer. At times it was fast scan. It varied according to person.

John: Over the entire period there were several different detectors or was there a progression?

Tim: It was more of a progression; when you got to the fast scan it was a combination. Fast scans were very quick.

Don B: Bed geometry was used from 1979 to 1986 at SRS; then it was fast scan. I have never found information that was perfectly clear that only fast scan was used after that. The Fastscan was placed in full production in 1989.

Tim: High-purity germanium detectors started at the end of 1989.

Joyce: Do you have lung counts with the germanium counter also?

Tim: We have those results when SRS prints out the spectra and sends; then yes.

Joyce: Wouldn't it be better to see Np itself if you have Np?

John: When the high purity germanium detector introduced in 1989, was the fast scan continued?

Tim: Fast scan use was continued. The use of the fast scan continued into the 2000s.

3. SC&A has not found any information on how NIOSH plans to justify the use of I-131 or Cr-51 for work such as Np target fabrication where there was Np exposure potential but where exposure potential for I-131 and Cr-51 would be highly unlikely or essentially non-existent. Has NIOSH validated the proposed method for such areas? If so, could NIOSH provide the validation data to SC&A?

Tim: Np was not exactly fresh. People in the 300 Area were also sent for WBC.

Arjun: Do we know time delay between neptunium separation and target fabrication in the 300 Area?

Tim: No, but it could be determined.

4. In regard to items 1 to 3, did NIOSH prepare sample Np-exposure-related dose reconstructions using the surrogate radionuclide data? If so, could NIOSH provide them to SC&A?

Tim: Other than what we have done in OTIB-81, I do not recall that we have done sample dose reconstructions.

Matt: We calculated hypothetical effective dose equivalents. Or rather we calculated 50-year committed organ doses.

Arjun: Can SC&A see these calculations?

Matt: I don't think we documented them in OTIB-81.

Tim: OTIB-81 is the coworker model for all the radionuclides. It is for SRS.

John: In view of that, are these other OTIBs going to be retired? Does OTIB-81 have sample DRs?

Tim: The reports that we published (RPRT-55, -56, -58, [ORAUT 2012a, 2012c, and 2012d]) were to address the issue of comparing construction workers with non-construction workers. They weren't intended to present the coworker model.

Arjun: I don't recall hearing that there was another coworker model document forthcoming. We are proceeding on the information that the published reports provide the coworker model approach the NIOSH intends to use.

Tim: I may have mentioned OTIB-81 in an email to Mark Griffon some months ago but I am not sure.

5. SC&A notes that there are no interviews referenced in ORAUT-RPRT-0056. Did NIOSH do any interviews of current or former workers regarding any aspect of neptunium work or exposure potential in the post-September 30, 1972 period? If so, could NIOSH provide the interview notes to SC&A? Along the same lines, does NIOSH have the names of at least some workers who definitely worked with neptunium in the various areas in the 1970s, 1980s, and 1990s?

Tim: We have not formally conducted interviews with workers who conducted neptunium work.

6. NIOSH has not specified any dose reconstruction method for Np past the late 1980s even though the SEC review period extends to 2007. Does NIOSH intend to do so?

Tim: OTIB-81 will go to 2006.

B. Thorium, Addendum 3 of the SEC-00103 Evaluation Report dated November 20, 2012.

1. NIOSH proposes to use bioassay data for the trivalent radionuclides Am, Cm, Cf for estimating thorium intake up to 1994 (Addendum 3, p. 28). In its Addendum 3 to the SEC-00103 Evaluation Report, NIOSH states that it is relying on this method since the procedure for extracting these trivalent actinides would also extract thorium (Addendum 3, p. 28). However, the paper referenced (Butler and Hall 1970) does not discuss the extraction of thorium with the three trivalent actinides. It states that thorium was extracted along with eight other actinides at high efficiency—over 90 percent for all actinides except uranium for which the efficiency was reported as 82%. The method was considered to be useful for gross alpha counting. However, SRS aimed to develop a method for counting Am, Cm, and Cf; the paper describes the process for separating these three. As reported by NIOSH (Addendum 3, Section 7.1.1.8), SRS developed a procedure to separate Pu, Np, and U from the extracted actinide mixture before counting for Am, Cm, and Cf. There is no discussion in the paper as to whether thorium was efficiently extracted along with the Am, Cm, and Cf. In fact, the paper did not concern itself further with thorium because "At this laboratory, thorium, berkelium, and einsteinium are not present in biological samples in sufficient quantities to require separation or routine identification by alpha spectrometry." (Butler and Hall, Analytical Chemistry, Vol. 42, No. 9, August 1970, SRDB 119808, p. 1075) Does NIOSH have any data on the thorium extraction efficiency of the process used at SRS to separate out Np, Pu, and U from Am, Cm, and Cf after 1970? If so, could NIOSH provide it to SC&A?

Tim: SRDB 86192 and 45959[15] both provide the procedure for Am, Cm, Cf. It is a DuPont procedure, DPSOL 47-206, for Am, Cm, Cf. Extraction efficiency was 97%. These procedures state that thorium will be included in the Am, Cm, Cf determination. The reference was from SRDB Ref ID 45959, pdf page 120 which states: "Limitation: Thorium will be included in the Am-Cm-Cf determination, but it is not normally present in significant quantities." The page also states the precision (at the 95% confidence level) for trivalent actinides is ±19% at the 6 pCi/l.5 liter level. NIOSH is continuing to research this question.

Arjun: Above 90% efficiencies were at the first step when nine radionuclides were extracted. The Am, Cm, and Cf were separated and there is the question of thorium extraction efficiency in this step. And thorium is a chemical analog of plutonium, so wouldn't some of it go in that stream?

Joyce: It doesn't actually provide the efficiency. It says thorium is a contaminant. It lists Am, Cm, Cf. We don't know the extraction efficiency of thorium relative to the other three. That is a key question.

Tim: They were not concerned with thorium coming through because they did not believe there was thorium exposure potential. So everything that was going to come through came through. It

[15] SRDB 86192 and 45959 are the same document and can be found in the Reference List as Westinghouse 1991.

states that thorium came through. Tim also noted during the call that the procedure used for trivalents changed in 1990; NIOSH intends to use the *in vivo* data to bound doses from 1990 forward rather than from 1995 forward.

2. Does NIOSH have the MDA for thorium in the Am, Cm, Cf stream? If so could NIOSH provide this data to SC&A?

Responses: MDA for Am, Cm, Cf is 0.3 dpm per 1.5 liter.

Arjun: But that does not give us the thorium MDA.

Joyce: If you are talking about just the count, that is one thing; it would be the same. But if you don't know the efficiency of extraction of thorium, then one can't actually determine the thorium MDA. The efficiency is the key question.

Arjun: It there a presumption that Th went along with Am, Cf, Cm?

Matt: The assumption is that the efficiency of thorium extraction is the same as that for the other three.

Arjun: But we don't know that for a fact.

Tim: We can get a radiochemist to make a determination about that [efficiency of thorium extraction].

3. NIOSH's report on estimation of doses due to exposure to the trivalent actinides, ORAUT-RPRT-0055 (July 20, 2012) indicates that NIOSH will use bioassay data for these radionuclides to estimate intakes. NIOSH is planning to use the same trivalent actinide monitoring data for estimating intakes for thorium until 1994. SRS did not concern itself with thorium in vitro bioassay monitoring after the mid-1950s. Does NIOSH have evidence that the workers who had exposure potential for thorium were monitored for Am, Cm, and Cf at the relevant time periods?

Arjun: When we reviewed Addendum 1 of the Evaluation Report for 300 Area thorium intake estimation, we had some concerns about NIOSH using the same bioassay data to estimate uranium and thorium intakes.

Tim: This is different than what you are referring to in the 300 Area. There we were using mass of uranium as surrogate for thorium based on same process for uranium and thorium. What we are proposing here is that in the dose reconstruction, we will look at the count and run the DR based on just Am, Cm, Cf, or Th and attribute the highest dose.

Thorium would typically be assigned in a few cases, such as bone where it results in the highest dose. One of the other three would typically dominate for other organs.

Joyce: That would not be so for lung dose. Thorium could be Type S and Am is always Type M; so in that case thorium lung dose would be higher.

John: So NIOSH would be assigning one dose based on the trivalent actinide bioassay.

Joyce: Is there a problem with super-estimating—that is, estimating doses that are too high to be plausible? For example, if you assume a worker worked thorium oxide, which is very insoluble, then you actually have Am in urine. If you interpret that as Type S thorium, you could have a super-estimation of dose, even though it is claimant favorable.

Liz: A coworker study would be run for Type M and Type S.

Joyce: But if you assume it is Type S thorium maybe you will over-estimate by 100 times or even 1,000 times. Is that reasonable?

Tim: I am not sure that will be the case since we have WBC data. MDA for WBC count would truncate the dose, but we would have to check into that. Also, there is one correction [to Addendum 3]. We have found a document that states that the transition to whole body counting was in 1990. We will modify the procedure [in Addendum 3] and use WBC data for thorium from 1990 onwards, rather than 1994 [as stated in Addendum 3].

4. NIOSH proposes to use in vivo data for thorium intake estimation from 1995 to 2007. NIOSH states that the chest counter that was used from 1989 onward could detect the 84.4 KeV Th-228 photo-peak and the 238.6 keV line for Pb-212. In this context NIOSH states that "if statistically significant activity was present in the individual worker examinations, then photopeaks of those energies would have been listed on the chest count report as *unidentified*. These *unidentified* peaks could have been resolved and identified as thorium during the report review process. Depending on the skill of the SRS HP analyst, the possibility exists that the association of the unidentified peaks with Th-232 may have been missed" (Addendum 3, p. 20, italics in the original; highlighting added). Did NIOSH find any cases where the spectral lines in question were actually identified as thorium? If so, how many such examples did NIOSH identify? Could NIOSH provide the data and the relevant worker information to SC&A for review?

Tim: We have not found any records where the chest count exceeded the MDA for either the Pb-212 peak or for unresolved and unidentified peaks. NIOSH has not found any peaks actually identified as thorium. This is not surprising because the potential for exposure is quite low. We have the thorium inventory data.

Joyce: My big problem is that when I look at some workers, most of the WBC counts were fast scans. So then you can't really capture the Pb-212 peak.

5. NIOSH has reported the MDA for Pb-212 as 0.15 nCi and proposes to assign this as missed dose for workers with thorium exposure potential unless there is evidence of an above MDA reading (Addendum 3, p. 31). How is NIOSH going to determine the identity of workers with thorium exposure potential? Also, SRDB 722 [Internal

Dosimetry 2001], referenced in Addendum 3, states that a mobile counter was also used at SRS. Was the Pb-212 MDA for that also 0.15 nCi or some other value?

Arjun: Joyce has noted the use of fast scans, so presumably MDA for that would be much higher.

Tim: We gave the MDA for the standard WBC; it was also used at SRS.

Joyce: Even today 0.15 nCi would be very very small for an MDA. The best ones even today have 0.24 nCi. You can't get 0.15 nCi.

Mike: It would be amazing if anyone had even 0.15 nCi, based on the very small amounts of thorium inventoried at SRS during the period.

Tim: The SRS facility was specially designed for whole body counting.

Joyce: The most important question is this: could they look at Pb-212 even if they were using a fast scan. Another issue is Pb-212 is after thoron so you don't know if it is from thoron or thorium. There is no mention of Ac-228, which would lead us to Th-232.

Tim: I don't see any peaks ever in fast scan data. What we typically see is the K-40 peak and occasional cesium peak if they [the workers] ate a lot of deer.

Joyce: So that is why I say it is geared to those kinds of radionuclides.

Tim: I think if there was an exposure you would see it. Note: we are investigating the fast scans in more detail.

Joyce: I don't know about that. What is the probability of a thorium worker being counted on a chest count or a fast scan?

Tim: Workers in 773-A were routinely counted.

Joyce: Every year?

Tim: Certain people have different monitoring frequencies. But after 1995, when 10 CFR 835 was issued, people with exposure potential of more than 100 mrem were monitored every year. Before 1995, the DOE RadCon manual was used [92 to 94]. DOE Order 5480.11 was used from 1990 to 1992. It was equivalent. We are proposing to start the use of WBC for thorium in 1990; the RadCon manual was much the same as [10 CFR] 835. DOE Order 5480 was equivalent. We are assuming the site complied with these regulations.

6. Has NIOSH found any in vivo data where the Pb-212 result was above the MDA? If so, would NIOSH provide the data to SC&A?

Tim: No.

7. Has NIOSH done any sample dose reconstructions for thorium using the methods proposed in Addendum 3 (bioassay data from 1973 to 1994 and in vivo data from 1995 to 2007)? If so, could NIOSH provide them to SC&A?

Tim: Only what is provided in the Evaluation Report. We have not done any sample dose reconstructions.

8. SRDB 98490 [Thorium Rooms, no date] contains information on rooms where thorium work was done. It is dated 2010 and appears to have been requested by you. Could you please provide the name of the author of this document?

Tim: That list was created in 2011 when Brant Ulsh, myself, Kathy Demers and Jack Beck were reviewing multiple logbooks. When we found mention of thorium, we wrote down the room number. So that document was produced as a combination of our work during that site visit. The time period that we examined was 1953–1959. I don't think it is relevant to the period of the present SEC investigation. So, this document, written in longhand, was created jointly by NIOSH/SC&A during logbook review at the site; it applied to 1953–1959.

Brad Clawson noted that he also participated in the review.

Ted: Regarding example dose reconstructions. It is normal procedure to do them in order to illustrate the methods proposed by NIOSH during its review of SECs. So if this is the new TIB coming out we would need sample dose reconstructions to go with it.

Tim: In my experience recent SEC reviews have not been doing sample dose reconstructions. I will consult with Jim and Stu and get back to you.

Ted: When procedures were complex, sample dose reconstructions have been done; it has been done when there is a question about the method. So, if there is a question about it, it should be done.

Tim: Again, I will have to get with Stu and Jim and get back to you.

ATTACHMENT B: WRITTEN ANSWERS PROVIDED BY NIOSH TO SRS SEC-RELATED QUESTIONS

NIOSH provided the following written clarifications to the SRS WG and SC&A on February 1, 2013, regarding points that SC&A raised about neptunium and thorium dose reconstruction approaches proposed by NIOSH for the Savannah River Site. The SC&A questions, sent to NIOSH on January 4, 2013, are reproduced verbatim prior to the answers.

Prepared by NIOSH and the ORAU Team

A. Neptunium dose estimation as specified in ORAUT-RPRT-0056, dated August 20, 2012

7. The neptunium dose reconstruction method proposed by NIOSH in ORAUT-RPRT-0056 proposes to use chest count data for certain radionuclides as suitable stand-ins (or surrogates) for neptunium-237, based on overlap of spectral lines. We did not find any information on how NIOSH plans to establish that the workers who were monitored for the surrogate radionuclides that were measured also had exposure potential to neptunium at the relevant times and places. Has NIOSH developed such information to show that the surrogate radionuclide data are indeed relevant for neptunium exposure potential at the appropriate times and places? If so, could NIOSH make the data available to SC&A?

   NIOSH Response: Workers who had a potential for Np-237 exposure worked in certain areas at SRS. The main areas were the 200 areas (Separations), 773 area (Savannah River Laboratory), and the 300 area (Materials Area). Workers in the areas typically received whole body counts on a routine basis. Unmonitored workers (unbadged) in these areas had a lower potential for exposure than monitored workers. Thus assignment of a coworker model dose is claimant favorable.

   The whole body count data for other radionuclides is being used as stated. However, it is important to distinguish between data based on actual intakes of surrogate radionuclides and data based on potentially mis-identified whole body count results. It is only that portion of the whole body count spectrum that is being used. This is not a surrogate method that is being proposed.

   In vivo bioassay (whole body counts) relies on gamma spectroscopy, using "regions of interest" to identify emissions from specific radionuclides. These regions of interest, which are simply a specific range of gamma energies, are typically interpreted as a particular nuclide but that does not mean that any detected counts couldn't be from a different radionuclide that has a similar energy gamma ray. Np-237 or its daughter, Pa-233, emit gammas of similar energies to those of I-131 and Cr-51, so the counts reported for each of these could also be due to Np-237. For example, throughout the 1960s the net count in the 300–400 keV range was used to calculate an I-131 activity, but Pa-233 also emits several gamma rays in this region so the net count can also be used to determine a Np-237 activity. SRS interpreted the region as I-131 only because that was the more

likely nuclide. This methodology is not dependent on workers having exposure potential for those other radionuclides.

8. Timeliness of monitoring is particularly important in the case of the surrogate radionuclides proposed for neptunium, since I-131 and Cr-51 are relatively short-lived having half-lives of 8 and 28 days (rounded), respectively. Has NIOSH compiled validation data regarding the times of chest counting compared to the periods of Np-237 exposure potential to ensure that the data are relevant for estimating Np-237 intake? If so, could NIOSH provide the validation data to SC&A?

   NIOSH Response: As discussed in the response to Question 1 above, surrogate radionuclide data is not being used. The half-lives of I-131 and Cr-51 are not pertinent since the methodology does not depend on worker having exposure to those radionuclides.

9. SC&A has not found any information on how NIOSH plans to justify the use of I-131 or Cr-51 for work such as Np target fabrication where there was Np exposure potential but where exposure potential for I-131 and Cr-51 would be highly unlikely or essentially non-existent. Has NIOSH validated the proposed method for such areas? If so, could NIOSH provide the validation data to SC&A?

   NIOSH Response: As discussed in the response to Question 1 above, surrogate radionuclide data is not being used. The exposure potential of Np-237 workers to I-131 and Cr-51 is not pertinent since the methodology does not depend on worker having exposure to those radionuclides. On the original whole body counts form, associated with the 40-cm arc detector, and used 1960–1974, there was an ROI labeled Np-237 at 230–290 keV. From an in vivo counting perspective use of this region didn't seem appropriate to us. Np-237 has gammas with only <0.5% abundance and they are not in the 230–290 keV region. Pa-233 has a 272 keV line but only 0.3% abundance. The best ROI to use is the 300–400 keV with several lines from Pa-233 with reasonable abundance. It is possible, but documentation has not been found, that SRS was worried about interference from I-131 and Cr-51 and did not want to assign counts from the latter radionuclides to Np-237. It is theoretically possible to calibrate the whole body detector for measuring a radionuclide in an ROI just below the principal ROI based on scatter of some gammas from their total energy to the lesser energy. This is not optimal but possible and it appears that is what SRS did for the 40-cm arc detector. The MDA was not good however. SRS did not label a specific energy region of interest for Np-237 from 1975 on so the best region was chosen, which differed slightly depending on the reporting format (300–400 keV for one format and 290–349 keV for another). Because for the EEOICPA it is claimant favorable to assign all of the counts in the preferred 300–400-keV or 290–349-keV ROI to Np-237 even if some were from I-131 or Cr-51, use of the higher energy ROI for Np-237 made better sense than use of the 230–290 keV region. This approach was used in the coworker analysis for 1970 to 1989. Urine data were used in the coworker analysis for years prior to 1970 and for after 1990.

Use of chest count data was investigated but the site did not report results in the energy range applicable to Np-237 for the years of interest so chest count data could not be used.

10. In regard to items 1 to 3, did NIOSH prepare sample Np-exposure-related dose reconstructions using the surrogate radionuclide data? If so, could NIOSH provide them to SC&A?

    NIOSH Response: As discussed in the response to Question 1 above, surrogate radionuclide data is not being used. What is being used is Np-237 (and decay product) data recorded in the chest count spectrum as other radionuclides.

11. SC&A notes that there are no interviews referenced in ORAUT-RPRT-0056. Did NIOSH do any interviews of current or former workers regarding any aspect of neptunium work or exposure potential in the post-September 30, 1972 period? If so, could NIOSH provide the interview notes to SC&A? Along the same lines, does NIOSH have the names of at least some workers who definitely worked with neptunium in the various areas in the 1970s, 1980s, and 1990s?

    NIOSH Response: NIOSH has not interviewed former workers or staff in relation to neptunium work.

12. NIOSH has not specified any dose reconstruction method for Np past the late 1980s even though the SEC review period extends to 2007. Does NIOSH intend to do so?

    NIOSH Response: The purpose of ORAUT-RPRT-0056 is to conduct a strata comparison of Np-237 intakes for various classifications of workers. The dose reconstruction method, an excerpt of which is contained in ORAUT-RPRT-0056, is actually contained in ORAUT-OTIB-0081 (Draft), the internal coworker study for SRS. ORAUT-OTIB-0081 provides Np-237 coworker intake rates for 1961 through 2006.

B. Thorium, Addendum 3 of the SEC-00103 Evaluation Report dated November 20, 2012

9. NIOSH proposes to use bioassay data for the trivalent radionuclides Am, Cm, Cf for estimating thorium intake up to 1994 (Addendum 3, p. 28). In its Addendum 3 to the SEC-00103 Evaluation Report, NIOSH states that it is relying on this method since the procedure for extracting these trivalent actinides would also extract thorium (Addendum 3, p. 28). However, the paper referenced (Butler and Hall 1970) does not discuss the extraction of thorium with the three trivalent actinides. It states that thorium was extracted along with eight other actinides at high efficiency—over 90 percent for all actinides except uranium for which the efficiency was reported as 82%. The method was considered to be useful for gross alpha counting. However, SRS aimed to develop a method for counting Am, Cm, and Cf; the paper describes the process for separating these three. As reported by NIOSH (Addendum 3, Section 7.1.1.8), SRS developed a procedure to separate Pu, Np, and U from the extracted actinide mixture before counting

for Am, Cm, and Cf. There is no discussion in the paper as to whether thorium was efficiently extracted along with the Am, Cm, and Cf. In fact, the paper did not concern itself further with thorium because "At this laboratory, thorium, berkelium, and einsteinium are not present in biological samples in sufficient quantities to require separation or routine identification by alpha spectrometry." (Butler and Hall, Analytical Chemistry, Vol. 42, No. 9, August 1970, SRDB 119808, p. 1075) Does NIOSH have any data on the thorium extraction efficiency of the process used at SRS to separate out Np, Pu, and U from Am, Cm, and Cf after 1970?

NIOSH Response: Butler and Hall, 1970 list the extraction efficiency for thorium as 97% (SRDB 119808 Table 1). SRS used the same procedure through 1989. SRS utilized the same liquid ion exchange procedure in the determination of the concentration of six actinides along with thorium. Plutonium, neptunium, and uranium were exchanged to TIOA (tri-isooctylamine) and were removed individually from the organic depending on the strip solution used. Americium, curium, californium and thorium were extracted from the aqueous with bidentate (dibutyl N,N-diethyl carbamylphosphonate) (SRDB Ref ID 86192, pdf page 120). There is a limitation stated that thorium is not normally present in significant quantities; this is not due to a limitation in the procedure's ability to extract thorium (as indicated above to be 97%), but rather just an observation that is due to the miniscule amount of thorium exposure or thorium signal. The bioassay procedure was used from at least 1970 through 1989. Thorium is specifically referenced as a component of the Am result as late as 1987 in SRDB Ref ID 45959, pdf page 120. Since publication of the third addendum, NIOSH has determined that the procedure was replaced starting in 1990 (SRDB Ref ID 10931, [Westinghouse 1995] pdf page 79) NIOSH intends to use the chest counting data starting in 1990 through 2007 to bound potential intakes in those years.

If so, could NIOSH provide it to SC&A?

NIOSH Response: The efficiency of the procedure for thorium was reported to be 97%. The procedure had an MDA of 0.3 dpm per 1.5 liter for enriched uranium, americium, curium, californium and thorium.

10. Does NIOSH have the MDA for thorium in the Am, Cm, Cf stream? If so could NIOSH provide this data to SC&A?

    NIOSH Response: The MDA for thorium was 0.3 dpm per 1.5, the same as for americium, curium, californium since the method was counting gross alpha.

11. NIOSH's report on estimation of doses due to exposure to the trivalent actinides, ORAUT-RPRT-0055 (July 20, 2012) indicates that NIOSH will use bioassay data for these radionuclides to estimate intakes. NIOSH is planning to use the same trivalent actinide monitoring data for estimating intakes for thorium until 1994. SRS did not concern itself with thorium in vitro bioassay monitoring after the mid-1950s. Does

NIOSH have evidence that the workers who had exposure potential for thorium were monitored for Am, Cm, and Cf at the relevant time periods?

NIOSH response: Most of the Am, Cm, Cf work at SRS was conducted in the 773A building at SRS. The bulk of the unencapsulated thorium inventory at SRS was also handled in Building 773A. As a result, workers in the large radiochemistry building would be exposed to Am, Cm, Cf, and thorium.

For example, work with Pu, Am, Cm and Cf was performed in hot cells in Building 773-A. Dissolution tests and off gas tests with thorium irradiated fuels during the Thorium Fuel Cycle studies were also conducted in the hot cells of 773-A. Potential exposures to these radionuclides were limited by the hot cell controlling environment. In the 1980s, some amount of testing with thorium on the welding agents was performed on plutonium heat sources, also in enclosed environments. Still, workers involved in hot cell work were monitored by bioassay for Pu and trivalent intakes. Most of these workers would have also performed the testing with thorium. Given the population of workers sampled by trivalent bioassay, that data should bound doses to workers that also worked with small amounts of thorium.

In ORAUT-OTIB-0075 (ORAUT 2009), arguments were presented to support the practice of treating a claimant dataset as a simple random sample from the population of all monitored workers. One potential problem posed by using a claimant dataset is that workers involved in incidents usually submit more samples than workers who submit only routine (non-incident-related) samples. This is problematic because a small number of workers involved in incidents can dominate the claimant sample in a given year through the sheer number of samples submitted and because the samples in the dataset are no longer independent of each other. At SRS, the small population of workers subject to bioassay testing results in a similar problem. To compensate for the unequal number of samples submitted by workers, the “one person, one sample” (OPOS) technique is used, in which only one result is used for each person for each radionuclide for a given year. The OPOS statistic is calculated using the maximum possible mean methodology. Potential exposure to internal intakes of thorium was mostly limited to workers in Building 773-A. Coworker thorium intakes will be assigned to those who worked in Building 773-A.

12. NIOSH proposes to use in vivo data for thorium intake estimation from 1995 to 2007. NIOSH states that the chest counter that was used from 1989 onward could detect the 84.4 KeV Th-228 photo-peak and the 238.6 keV line for Pb-212. In this context, NIOSH states that “if statistically significant activity was present in the individual worker examinations, then photo peaks of those energies would have been listed on the chest count report as *unidentified*. These *unidentified* peaks would have been resolved and identified as thorium during the report review process. Depending on the skill of the SRS HP analyst, the possibility exists that the association of the unidentified peaks with Th-232 may have been missed.” (Addendum 3, p. 20, italics in the original; highlighting

added). Did NIOSH find any cases where the spectral lines in question were actually identified as thorium? If so, how many such examples did NIOSH identify? Could NIOSH provide the data and the relevant worker information to SC&A for review?

NIOSH response: As stated in the response to question B.1 above, NIOSH intends to use chest counting data starting in 1990 rather than 1995. NIOSH has found no records where a chest count exceeded the stated MDA at the 84.4 keV peak. In the records reviewed by NIOSH, no results were reported as exceeding the MDA at the 238.6 keV peak. Assuming such may have occurred, unresolved *unidentified* peaks would be listed on the *in vivo* (chest) count reports available to the NIOSH dose reconstructor for resolution when reviewing the individual's dose records. Instructions for this review will be added to the SRS technical basis document.

13. NIOSH has reported the MDA for Pb-212 as 0.15 nCi and proposes to assign this as missed dose for workers with thorium exposure potential, unless there is evidence of an above MDA reading (Addendum 3, p. 31). How is NIOSH going to determine the identity of workers with thorium exposure potential? Also, SRDB 722 [Internal Dosimetry 2001], referenced in Addendum 3, states that a mobile counter was also used at SRS. Was the Pb-212 MDA for that also 0.15 nCi or some other value?

    NIOSH response: The assumptions and model given in the third ER addendum only apply to measurements made by the chest counter in Building 735-4B. Those records are identified as being chest counts. Due to the practice of Chapter 11 and 10 C.F.R. pt. 835, workers with potential for exposure of 100 mrem in a year were monitored by requirement. Data given in addendum Table 5-3 of the addendum show maximum inventories over the period (between 200 to 300 kg); fairly small quantities that were mostly worked with in labs. Health Physics would have evaluated the potential for intake and dose to determine if monitoring for thorium was required, either by bioassay or air monitoring (SRDB 116010, [Interview 2012]).

14. Has NIOSH found any in vivo data where the Pb-212 result was above the MDA? If so, would NIOSH provide the data to SC&A?

    NIOSH response: In the records reviewed by NIOSH, no results were reported as exceeding the MDA at the 238.6 keV peak.

15. Has NIOSH done any sample dose reconstructions for thorium using the methods proposed in Addendum 3 (bioassay data from 1973 to 1994 and in vivo data from 1995 to 2007)? If so, could NIOSH provide them to SC&A?

    NIOSH response: NIOSH has not performed a complete dose reconstruction using those methods but only the organ dose reconstructions presented in the third addendum.

16. SRDB 98490 contains information on rooms where thorium work was done. It is dated 2010 and appears to have been requested by you. Could you please provide the name of the author of this document?

    NIOSH response: The referenced document (SRDB 98490) was assembled by Tim Taulbee, Jack Beck, Brant Ulsh, and Kathy Demers during a search of SRS documents in 2011. Rooms were gathered from review of Health Physics survey records and logbooks authored by Health Physics staff. This document only pertains to the period covered by the second addendum to the ER.

ATTACHMENT C: CONFIDENCE LEVELS AND POWER WHEN COMPARING TWO GROUPS OF WORKERS

NIOSH has not demonstrated that 30 samples from each group will provide sufficient power to detect differences between the two groups of workers. A Crystal Ball program was used to simulate the power of the WRS test using lognormal data with nondetects. The test compared 30 samples from each of two lognormal distributions, $X_1 \sim LN(0, \sigma)$ and $X_2 \sim LN(1, \sigma)$. These distributions have the same shape and same geometric standard deviations of $GSD_1=GSD_2=e^{\sigma}$, but different geometric means. The ratio of their geometric means is $GM_2/GM_1=e=2.73$, hence distribution 2 is a factor of 2.73 higher than distribution 1. The simulation used a detection limit of 0.5.

The simulation is designed to determine the power of the WRS test to detect differences for different values of the GSD and the confidence level used in the test. The simulation was conducted for 6 values of GSD = 2, 3, 4, 5, 6 and 7. Four values of the Type 1 error rate α were used for the WRS test: 0.05, 0.10, 0.20 and 0.25. The confidence levels for these test scenarios are 95%, 90%, 80% and 75%, respectively.

The results of the simulation are shown in Figure 1 and Table 1. Figure 1 shows the Type 2 error rate (β) on the vertical axis. The four values of Type 1 error rate (α) and the 6 values of the GSD are shown on the base plane of the plot. The left-most ribbon plot for α=0.05 shows the power for a WRS test conducted with a confidence level of 95%. Note that this value of confidence was used by NIOSH for the hypothesis tests reported in RPRT-0056. The value of the Type 2 error rate (β) rises from negligible values for small GSDs up to an error rate of 40% with a GSD of 7. If the Type 2 error rate is required to be less than 10%, the test can only achieve this level of performance when the GSD is less than 4. When the 95% confidence level test is used for distributions with GSDs higher than 4, the Type 2 error rate rises from 27% (β=0.27) at a GSD of 5 to as high as 42% (β=0.42) at a GSD of 7.

More relaxed values of the Type 1 error rates of 0.10, 0.20, and 0.25 (confidence levels of 90%, 80% and 75%, respectively) are plotted on the remaining three ribbons. A test with 90% confidence (α=0.10) can achieve a Type 2 error rate of less than 10% only when the GSD is less than 5. A test with 80% confidence (α=0.20) can achieve a Type 2 error rate of less than 10% only when the GSD is less than 6. A test with 75% confidence (α=0.25) can achieve a Type 2 error rate of less than 10% only when the GSD is less than 7.

Figure 2 and Table 2 show the effects of a higher detection limit when the WRS test is used to compare the same two lognormal distributions. The detection limit is raised to 4 in this simulation, increasing the percentage of nondetects to a range from 67% to 84%, depending on the GSD selected. Comparing the ribbons for α=0.05, the effect of a higher detection limit is to increase the Type 2 error rate from 4.3% to over 19% at a GSD of 3. At a high GSD of 7, the Type 2 error rate exceeds 50%.

These results demonstrate that the selection of a specific value of 30 samples for the minimum required sample size may not provide adequate power in cases with high GSDs. The problem is magnified when there are a larger percentage of nondetects. If the confidence level of the test is

relaxed, the WRS test will provide adequate power for a larger range of GSD values. The shaded areas in Tables 1 and 2 indicate the cases where the Type 2 error rate is less than 15%. A higher detection limit reduces the range of GSDs that will provide adequate power. With a minimum of 30 samples in each group and a relatively small percentage of nondetects (i.e., from 8% to 28% as in Table 1), a test with confidence level of 80% (α=0.20) will retain adequate power ($\beta \leq 0.15$) for GSDs ranging as high as 7. However, when the percentage of nondetects is large (from 67% to 84% as in Table 2), a sample size of 30 in each group may be inadequate, especially when confidence level is as high as 95%. With a sample size of 30 and a high detection limit in Table 2, the Type 2 error rate was greater than 0.15 from all GSDs greater than 2.

Table 3 shows the ratio of the Type 2 error rates for the high-detection-limit versus the low-detection-limit scenarios. The ratio ranges from a low of 1.3 for high GSD values to a high of over a factor of 9 for the low GSD scenarios. In relative terms, changing the value of the detection limit makes less of a difference when there is a high degree of variation in the samples. Large increases in the Type 2 error rate are seen for typical GSDs in the 3 to 4 range where the Type 2 error rate is increased by at least a factor of 2.

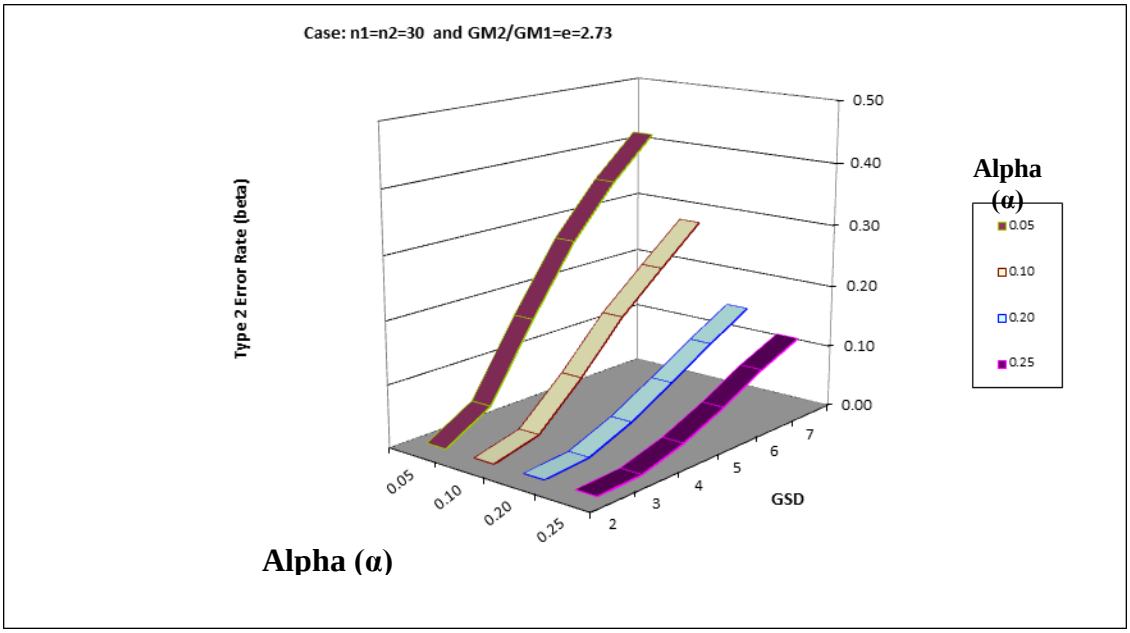

Figure 1. Type 2 Error Rate (β) of WRS Test using 30 Samples from Lognormal Distributions with a Low Detection Limit for Selected Values of Alpha

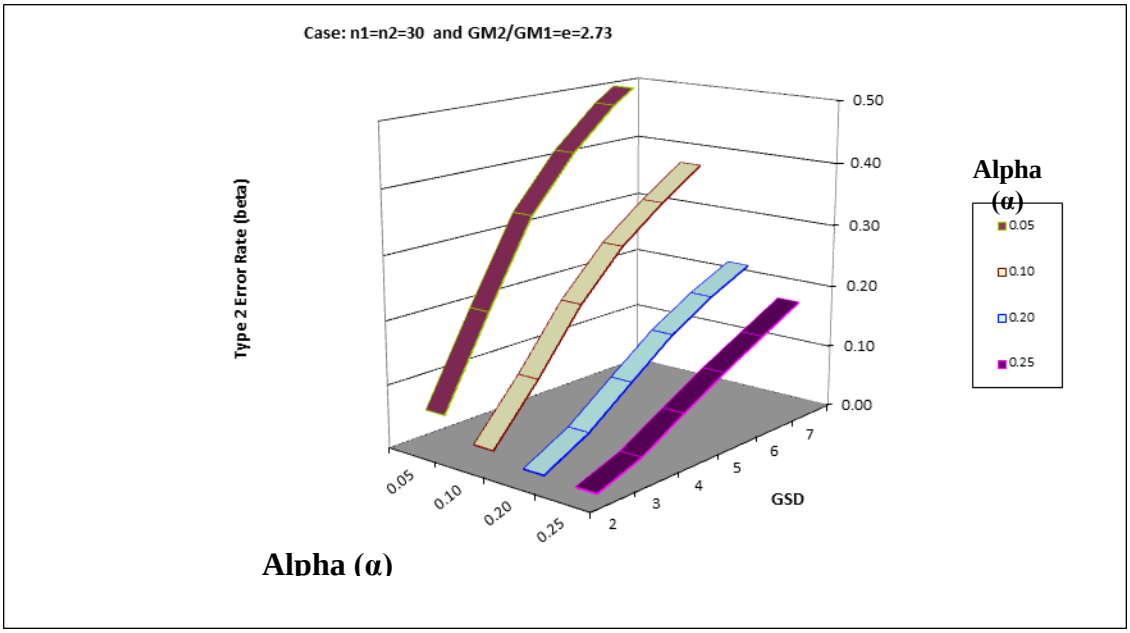

Figure 2. Type 2 Error Rate (β) of WRS Test using 30 Samples from Lognormal Distributions with a High Detection Limit for Selected Values of Alpha

Table 1. Type 2 Error Rate (β) of WRS Test using 30 Samples from Lognormal Distributions with a Low Detection Limit for Selected Values of Alpha ($n_1=n_2=30$ and $GM_2/GM_1 = 2.73$)

Low LOD=0.5	GSD					
α	7	6	5	4	3	2
0.05	0.416	0.351	0.269	0.161	0.043	< 0.001
0.10	0.280	0.221	0.161	0.085	0.019	< 0.001
0.20	0.150	0.113	0.073	0.035	0.006	< 0.001
0.25	0.118	0.090	0.054	0.024	0.003	< 0.001
% Nondetects	28	26	24	21	16	8

Note: Shaded area indicates cases with β < 0.15.

Table 2. Type 2 Error Rate (β) of WRS Test using 30 Samples from Lognormal Distributions with a High Detection Limit for Selected Values of Alpha ($n_1=n_2=30$ and $GM_2/GM_1 = 2.73$)

High LOD=4.0	GSD					
α	7	6	5	4	3	2
0.05	0.525	0.477	0.413	0.328	0.194	0.054
0.10	0.376	0.330	0.276	0.203	0.107	0.021
0.20	0.223	0.191	0.151	0.098	0.045	0.007
0.25	0.179	0.144	0.109	0.071	0.030	0.004
% Nondetects	67	68	70	73	77	84

Note: Shaded area indicates cases with β < 0.15.

Table 3. Ratio of Type 2 Error Rates of WRS Test for High versus Low Detection Limit for Selected Values of Alpha

RATIO=High/Low	GSD					
α	7	6	5	4	3	2
0.05	1.3	1.4	1.5	2.0	4.6	--
0.10	1.3	1.5	1.7	2.4	5.8	--
0.20	1.5	1.7	2.1	2.8	7.8	--
0.25	1.5	1.6	2.0	3.0	9.1	--

-- Not calculated

ATTACHMENT D: INTERNAL MEMORANDUM

Date: June 11, 2013
To: Arjun Makhijani, John Stiver
From: Patrick Kelly

Subject: Review of *White Paper for the Savannah River Site Extraction Efficiency of Thorium in Bidentate, Revision 00, March 8, 2013*

As you requested I have reviewed the White Paper that you provided that evaluates the chemical behavior of thorium (Th) in the Savannah River Site (SRS) analytical procedure. Specifically, the evaluation focused on whether Th would have been measured as part of the analytical fraction that contains americium (Am), curium (Cm) and californium (Cf), or if Th would follow the analytical fraction that contains uranium (U), plutonium (Pu) and neptunium (Np).

As stated in the white paper, the behavior of Th in a chloride system is well described in National Academy of Sciences publications NAS-NS-3050, *The Radiochemistry of Uranium* (Gindler 1962, page 177). This clearly addresses the extraction of Th and U (among other species) from the solvent used in the SRS procedure (TIOA-xylene) in a chloride system, and, as shown in Figure 1, Th does not extract under these conditions.

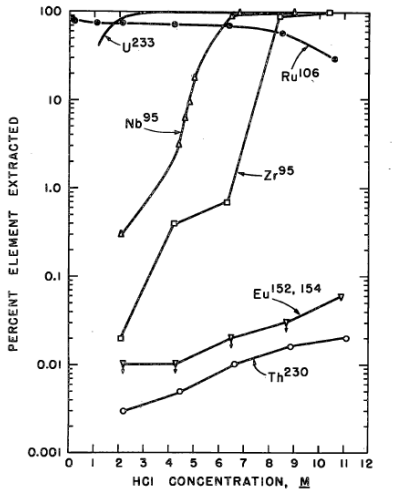

Figure 53. The extraction of U^{233}, Th^{230}, and fission products by 5% (w/v) triisooctylamine in xylene as a function of HCl concentration. After F. L. Moore, reference 475. Conditions: Equal phase volumes extracted for two minutes at room temperature (24°C.).

Figure 1: Thorium Extraction as a Function of HCL Concentration (Gindler 1962)

Specifically, Th does not make an anionic chloride complex, and, unlike Pu, Th will not extract in TIOA-xylene in a chloride system. Any Th in the sample would remain in the aqueous phase with the Am, Cm and Cf fraction. There are simply no conditions in which Th in HCl would be extracted. Moore (1960) speaks directly to this by showing that Th does not form anionic species in a chloride system, as shown in Table 1, which confirms that approximately 0.01% of the Th would extract in TIOA-xylene, the solvent used in the SRS procedure.

Table 1: Thorium Extraction as Described By Moore (1960)

Table V

Extraction of Thorium-230 (Ionium) Tracer
From Hydrochloric Acid With 5%
Triisooctylamine-Xylene

HCl, M	Th^{230} Extracted, %
2.2	0.003
4.5	0.005
6.7	0.010
8.9	0.016.
11.1	0.020

Apparently, concerns have been expressed that Th would actually behave like Pu and be removed during the first extraction step of the procedure, since Th is often considered a surrogate for Pu. This may be based at least in part on the behavior of Th and Pu in a nitrate system when, under specific conditions, the Th-Pu fraction can be eluted together (Holloway and Hayes 1982).

Regarding the extraction efficiency, Butler and Hall 1970, clearly states the Am, Cm, Cf, and Th in the second extraction in the procedure were all extracted with over 90% efficiency. In 8 N HCl solutions, the resulting efficiency of the procedure for Th extraction is stated to be about 97%. While it is difficult to assign a specific value to the Th extraction efficiency, there is no doubt that Th would follow the Am, Cm and Cf fraction, and not the U, Pu, and Np fraction under the conditions described in the white paper.

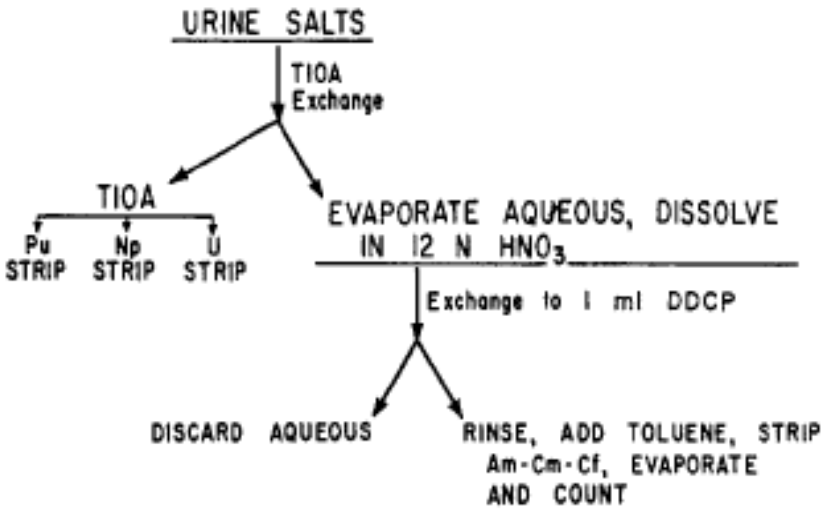

Figure 2: TIOA-DDCP Actinide Procedure as Provided By Butler and Hall (1970)

References

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Moore, F.L., 1960. *Liquid-liquid Extraction with High-molecular-weight Amines*, Oak Ridge National Laboratory, National Academy of Sciences, National Research Council, NASD-NS-3101. December 15, 1960.

ATTACHMENT E: EXAMPLES OF BIOASSAY SAMPLES AFTER CHELATION USED IN OPOS VALUES

Worker	DTPA Date(s)	Intake Date (if known)	Contaminants, Intake Type	Relevant Bioassay Dates	Bioassay Used in OPOS Calculation	Additional Comments
1	3/17/84	3/17/84	Pu-239/Am-241	3/18, 3/19, 3/30, 3/31	Yes	Worker has no other bioassay samples in 1984.
2	9/27/73	9/27/73	Pu-239	9/27, 9/28, 10/1, 10/8 –10/10	Yes	Worker has 3 additional bioassay results in 1973 in January, May and July.
3	12/30/86	12/30/86	Pu-239/Am-241	12/30, 12/31, 1/3–1/10, 1/12	Yes	Relevant bioassay results used in both the 1986 and 1987-1989 OPOS calculations
4	7/10/85	7/10/85	Pu-239, Wound	7/10–7/13, 7/15–7/18	Yes	Worker also had 2 samples on 8/31 and 9/1.
5	10/21/87	10/21/87	Pu-239	10/21–10/27	Yes	Remarks in database contains notation: "Dumped 12/8/87" No other bioassay exists for this worker in the database.
6	12/4/75	12/4/75	Pu-239/Am-241, Inhalation	12/4, 12/5, 12/9–12/11	Yes	Worker had one other bioassay result for 1975: 0 dpm/1.5L on 10/30/75
7	4/18/75	4/18/75	Pu-239, Inhalation	4/18, 4/19, 4/21, 4/24	Yes	Worker had no other bioassay results in 1975
8	1/27/82, 1/29/82	1/27/82	Pu/Am, Wound	1/28 –1/30	Yes	Worker had no other bioassay results in the database.
9	12/12/85	11/19/85	Pu-239/Am-241/Cm-244, Inhalation	12/12–12/14, 12/20, 12/29, 12/30	Yes	Worker also has samples in January 1986 that were negative
10	8/23/79	8/23/79	Am-241/Cm-242	8/23, 8/27–8/31, 9/4	Yes	Results on 8/23 listed "Report" values that were 3x higher than the averaged dpm/1.5L values.
11	5/9/86	5/8/86	Pu-239/Am-241, Wound	N/A	N/A	Worker had 2 samples taken on 2/9/87, no other bioassay results identified
12	9/4/84	9/4/84	Pu-239/Am-241, Inhalation	9/4–9/7, 9/11, 9/13, 9/18, 9/21	Yes	Worker also had samples in mid to late October and December of 1984
13	10/25/79	10/25/79	Pu-239/Am-241, Inhalation	10/26–10/29, 11/1, 11/2	Yes	Worker had no other bioassay samples in 1979.
14	2/8/88	2/8/88	Pu-239/Am-241, Inhalation	2/9–2/16, 2/24–2/26	Yes	Worker also had samples in late March 1988.

Worker	DTPA Date(s)	Intake Date (if known)	Contaminants, Intake Type	Relevant Bioassay Dates	Bioassay Used in OPOS Calculation	Additional Comments
15	3/14/73	3/14/73	Pu-239	3/15, 3/16, 3/18, 3/19	Yes	Worker also had a sample in mid May 1973.
16	4/12/74, 4/19/74	Unknown	Cm-244, Zr-95, Pu-239	4/12–4/22, 4/29–5/1, 5/7, 5/8, 5/16	Yes	Worker had 3 other samples in 1974 (2/4, 6/12. 10/24)
17	9/4/84	9/4/84	Pu-239/Am-241, Inhalation	9/5–9/7, 9/11, 9/18, 9/19	Yes	Worker also had 7 samples from 10/18 – 12/16
18	1/18/73	1/18/73	Pu-239/Am-241, Inhalation	1/19, 1/22, 1/23, 1/30 –2/1	Yes	Worker also had samples on 2/28, 3/1, 3/2 and 3/19
19	N/A	11/15/77	Cm-244	11/15–11/17, 11/21, 11/22, 11/28–12/2, 12/5, 12/6, 12/9	Yes	Worker also had a bioassay sample on 7/14/77
20	5/8/75	5/7/75	Pu-239/Am-241, Inhalation	5/8–5/11, 5/14, 5/25, 5/26	Yes	Worker also had one sample on 12/4/75
21	4/18/74	4/18/74	Cm-244, Inhalation	4/18, 4/19, 4/26, 5/3	Yes	Worker had numerous samples both before and after the incident in 1974.
	1/25/78	1/25/78	Cm-244/Am-241, Inhalation	1/26–1/28, 2/1, 2/6, 2/8	Yes	Worker had 3 additional samples in July and October of 1978
22	10/25/79	10/25/79	Pu-239/Am-241, Inhalation	10/26–10/31	Yes	Worker has no other bioassay results in 1979.
23	1/10/84	1/10/84	Cm-244	1/11–1/13, 1/15, 1/16, 1/26, 1/31	Yes	Worker has no other bioassay results for 1984.
24	10/16/73	10/16/73	Cm-244, Inhalation	10/16–10/18, 10/24–10/26, 10/29, 10/30	Yes	Worker has two additional samples on 12/11/1973.
25	3/14/73	3/14/73	Pu-239, Inhalation	3/14–3/18	Yes	Worker also had a sample on 2/14 and 7/13 in 1973.
26	1/18/73	1/18/73	Pu-239/Am-241, Inhalation	1/19, 1/22, 1/25, 1/31, 2/1, 2/26–2/28, 3/28	Yes	Worker has no other bioassay samples contained in database.
27	10/4/85	10/4/85	Pu-239/Am-241, Inhalation	10/6–10/10, 10/12, 10/14–10/18	Yes	Worker has no other bioassay samples contained in database.
28	4/18/74	4/18/74	Cm-244	4/18, 4/24, 5/9, 5/22, 5/23, 6/11–6/14, 6/17–6/21, 7/1, 7/15, 7/24	Yes	Worker also has a sample on 1/5/1974
	10/30/74	Unknown	Cm-244	11/4–11/8, 11/19–11/22	Yes	
	1/25/78	1/25/78	Cm-244	1/25–1/27, 1/30, 1/31, 2/8	Yes	Worker has two other bioassay samples in 1978 (1/16 and 9/28)

Worker	DTPA Date(s)	Intake Date (if known)	Contaminants, Intake Type	Relevant Bioassay Dates	Bioassay Used in OPOS Calculation	Additional Comments
29	4/12/74, 4/19/74	4/11/74	Cm-244/Zr-95/Pu-239	4/12–4/22, 4/29 –5/1, 5/6–5/8, 5/14–5/16	Yes	All bioassay samples for this worker in 1974 are labeled as incident samples.
	10/14/74	Unknown	Unknown	10/14–10/18, 10/21–10/23, 10/29–10/31	Yes	
30	11/19/85, 12/12/85	11/19/85	Cm-244/Pu-239/Am-241	11/21, 11/23–11/26, 12/10, 12/12–12/14, 12/19, 12/30, 12/31	Yes	All worker bioassay samples in 1985 are labeled as "incident."
31	4/18/74	4/18/74	Cm-244	4/18, 4/19, 4/24, 5/7, 5/8	Yes	Worker also had several bioassay results in June, July and October of 1974.
32	11/15/77	11/15/77	Cm-244, Inhalation	11/15, 11/17, 11/21, 11/22	Yes	Worker also had bioassay results on 9/9 and 11/7/1977.
33	12/12/85	11/19/85	Cm-244/Pu-239/Am-241, Inhalation	11/20, 11/23, 11/26, 12/7, 12/8, 12/13, 12/14, 12/20, 12/26, 12/27	Yes	Worker has no other bioassay results in the database.
34	7/30/1986	7/30/1986	Pu-239/Pu-240/Am-241	7/30–8/8, 8/11–8/15	Yes	Worker has no other bioassay results in 1986, OPOS result is negative.
35	1/18/73	Unknown	Pu-239/Am-241, Inhalation	1/19, 1/22–1/25, 2/1	Yes	Worker also had samples in late February and March 1973
36	2/11/80	2/11/80	Pu-238, Inhalation	2/11–2/13	Yes	There are no other bioassay samples for this worker in the database.
37	5/31/74	5/29/74	Pu-239, Inhalation	5/29, 6/1, 6/2	Yes	There are no other bioassay samples in 1974 for this worker.