

SEC Petition Evaluation Report Petition SEC-00103

Report Rev #: Addendum

Report Submittal Date: April 28, 2010

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Site Expert(s):	N/A

Petitioner Administrative Summary

Petition Under Evaluation

Petition #	Petition Type	Petition A Receipt Date	DOE/AWE Facility Name
SEC-00103	83.13	March 4, 2008	Savannah River Site (SRS)

Class Evaluated by NIOSH

All construction workers who worked in any area at the Savannah River Site from January 1, 1953 through December 31, 1965.

NIOSH-Proposed Class(es) to be Added to the SEC

None.

Related Petition Summary Information

SEC Petition Tracking #(s)	Petition Type	DOE/AWE Facility Name	Petition Status
NONE			

Related Evaluation Report Information

Report Title	DOE/AWE Facility Name
SEC Petition Evaluation Report, SEC-00103	Savannah River Site (SRS)

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SEC Petition Evaluation Reviewed By:	[Signature on file] <i>J. W. Neton</i>	5/4/2010 <i>Date</i>
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Addendum to Savannah River Site (SEC-00103) Special Exposure Cohort Evaluation Report

NIOSH presented a Special Exposure Cohort (SEC) evaluation report (NIOSH, 2008) regarding the Savannah River Site (SRS) to the Advisory Board on Radiation and Worker Health (Advisory Board) during the Advisory Board's meeting held from December 16-18, 2008. In its report, NIOSH evaluated the feasibility of reconstructing radiation doses of construction workers who worked in any area at SRS during the time period of January 1, 1950 through December 31, 2007. The feasibility of reconstructing doses received from thorium exposure from the start-up of thorium operations in 1953 through 1959 was reserved in the evaluation report while NIOSH continued to evaluate approaches for bounding doses from thorium exposures during that time period. This evaluation report addendum provides NIOSH's evaluation of the reserved thorium work, thus completing its evaluation of the worker class for SEC-00103.

NOTE: This Evaluation Report Addendum only addresses those sections in the Savannah River Site Evaluation Report that require discussion; therefore, the section numbering is not contiguous. The sections requiring additional thorium discussion begin below.

Petition Evaluation Report Addendum Summary

Class Evaluated by NIOSH (in this Addendum)

The feasibility of reconstructing doses received from thorium exposure from the start-up of thorium operations in 1953 through 1959 was reserved for further consideration in the original SEC-00103 evaluation report. During the subsequent evaluation performed for this evaluation report and addendum, NIOSH has determined that similar thorium operations were conducted at SRS through 1965; therefore, in this addendum NIOSH addresses the feasibility of bounding doses from thorium exposures received during the expanded time period of January 1, 1953 through December 31, 1965.

NIOSH-Proposed Class(es) to be Added to the SEC

NIOSH finds that potential radiation doses received from exposure to thorium at SRS from January 1, 1953 through December 31, 1965 can be reconstructed with sufficient accuracy. NIOSH intends to use uranium bioassay data as a substitute for thorium bioassay for the reconstructions. The uranium bioassay data was statistically modeled as lognormal distributions. The 50th percentile excretion rate obtained for each year was used to model the daily intake rates of uranium, by mass. Based on the process and data comparisons presented in this Addendum, a one-to-one ratio of thorium to uranium was assumed and daily thorium mass intake rates were derived for 1953 through 1965. Therefore, NIOSH maintains its recommendation that no portion of the class evaluated in SEC-00103 be included in the SEC.

3.3 NIOSH-Proposed Class(es) to be Added to the SEC

Based on its research, NIOSH has obtained monitoring data, source term information, and process information that allow dose reconstructions to be performed with sufficient accuracy. Based on its analysis of these available resources, NIOSH found no part of the class under evaluation for which it cannot estimate radiation doses with sufficient accuracy.

4.0 Data Sources Reviewed by NIOSH to Evaluate the Class

ATTRIBUTION: Section 4.0 and its related subsections were completed by Mike Mahathy, Oak Ridge Associated Universities. These conclusions were peer-reviewed by the individuals listed on the cover page. The rationales for all conclusions in this document are explained in the associated text.

NIOSH has obtained additional personal and area monitoring data for SRS since the initial evaluation report was published in November, 2008. Some of these data have been considered in the performance of this evaluation addendum and will be cited. NIOSH has also conducted additional interviews of former workers to obtain specific information on the use and monitoring of thorium.

4.3 Facility Employees and Experts

NIOSH interviewed former SRS employees in order to learn about health physics practices, internal and external dosimetry programs, dose recording practices, and radiological incidents pertinent to thorium use from 1953 through 1965.

- Personal Communication, 2009a, *Personal Communication with Two Former SRS Staff Members*, Interview by ORAU Team; December 17, 2008; SRDB Ref ID: 80280
- Personal Communication, 2009b, *Personal Communication with Two Former SRS Staff Members*, Interview by ORAU Team; December 17, 2008; SRDB Ref ID: 80281
- Personal Communication, 2009c, *Personal Communication with Former Nuclear Physicist*, Telephone Interview by ORAU Team; June 11, 2009; SRDB Ref ID: 73085
- Personal Communication, 2009d, *Personal Communication with Former Radiation Safety Technician*, Telephone Interview by ORAU Team; August 13, 2009; SRDB Ref ID: 73086

4.5 NIOSH Site Research Database

NIOSH has performed additional data captures at SRS since the initial evaluation report for the site was published in November 2008. As of August 2009, there were 3,677 documents in the Site Research Database (SRDB) pertaining to SRS; thus, approximately 1,400 additional documents have been captured, reviewed, and uploaded into the SRDB since that initial evaluation report. More than 100 documents pertained to thorium-processing, or to surface and air contamination conditions resulting from thorium.

NIOSH has also obtained additional personal monitoring records for about 175 former SRS workers who worked in the area where thorium was processed through 1965 (Area 300M). SRDB documents evaluated for relevance to the thorium issue include historical background on thorium operations, radiological monitoring data (surface and air concentrations, personnel external and internal exposures), and information on the radiological controls program, monthly reports, and incident documentation.

5.0 Radiological Operations Relevant to the Class Evaluated by NIOSH

The following subsections summarize SRS radiological operations involving thorium from January 1, 1953 through December 31, 1965 as well as the information available to NIOSH for characterizing particular processes and radioactive source materials. From available resources, NIOSH has gathered process and source descriptions, information regarding the identity and quantities of each radionuclide of concern, and information describing both the processes through which radiation exposures to construction workers may have occurred and the physical environment in which they may have occurred. The information NIOSH has included within its initial evaluation report and the report's addendum is intended only to be a summary of the available information.

5.1 Savannah River Site Plant and Process Descriptions

ATTRIBUTION: Section 5.1 and its related subsections were completed by Mike Mahathy, Oak Ridge Associated Universities; and Robert Morris, Mel Chew and Associates, Inc. These conclusions were peer-reviewed by the individuals listed on the cover page. The rationales for all conclusions in this document are explained in the associated text.

5.1.6 300 M-Area Fabrication Facilities

Natural thorium processes at SRS are well-documented (300/M Area, 2006) and were conducted using the common buildings, equipment, and processing steps used to make natural uranium slugs. SRS canned thorium metal slugs for Hanford fuel tests in Buildings 313-M and 320-M. The first thorium canning campaign took place from January 1953 through March 1953; about 320 1-kg slugs were canned. In 1954, SRS began research and development into a small-scale production process using an AlSi bath to produce and encapsulate thorium metal slugs for inclusion in reactor fuel rods and subsequent irradiation in the SRS reactors; about 1785 slugs were canned in 1954 and 100 were canned in the first half of 1955. By mid-1955, the effort shifted to large-scale inspection and

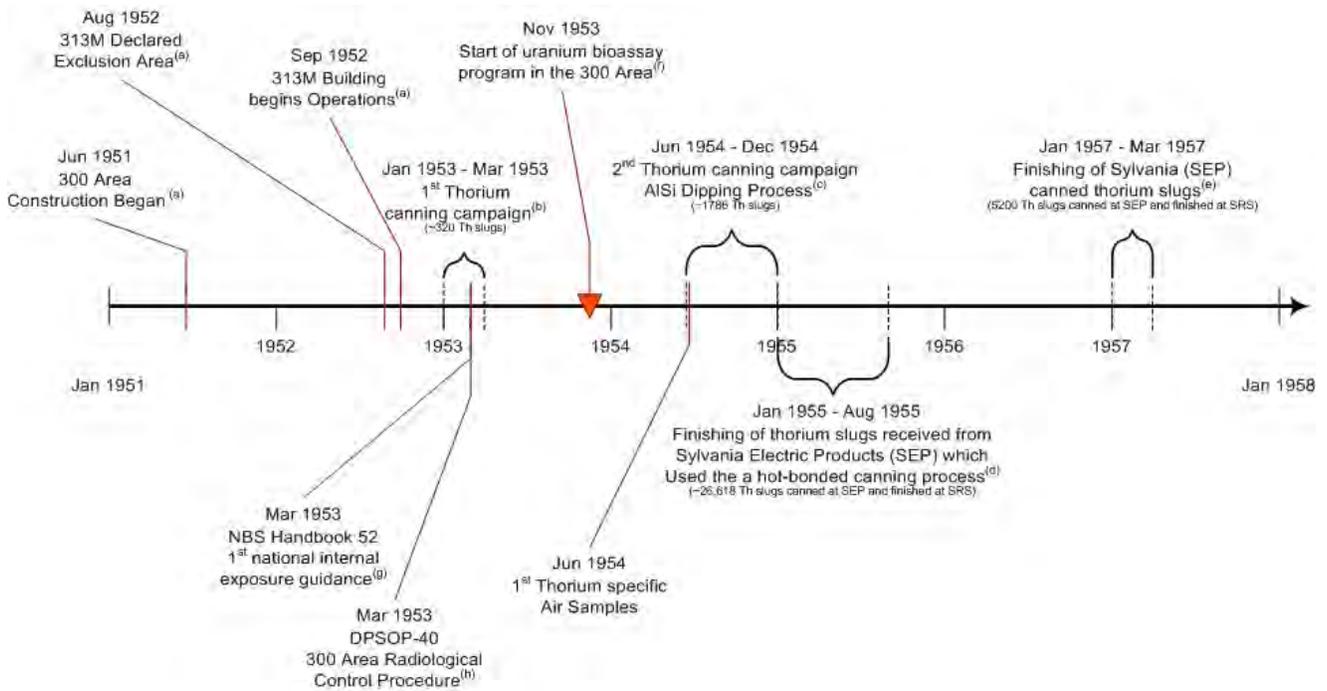
acceptance testing of canned thorium slugs that were canned off-site by Sylvania Electric Products (SEP) using a hot-bonded process. The canned slugs were fabricated into fuel assemblies that were irradiated in various reactor charges. An air sampling log sheet documents an air sample collected in 1955 in the Special Process Area of Building 313-M with the notation "welding 88 slugs [the code name for thorium slugs] and Y.C. [yellowcake uranium] about 2 feet from head of welding machine..." (Air Sample Log Sheets, 1955, pdf p. 60).

In September 1956, SRS received a request to irradiate five tons (~5000 slugs) of thorium to produce U-233 (Monthly Report, September 1956). The plan was to produce material that would then be shipped to the Oak Ridge National Laboratory (ORNL) in 0.75-ton batches with minimal cooling time (less than 30 days after discharge) to enable testing of radiation damage to extraction solvents and to determine radiation levels during various stages of the extraction process (Monthly Report, February 1957). Sylvania-Corning Nuclear Corporation (Sylcor) canned these thorium slugs (Monthly Report, September 1956). A total of 5200 canned slugs were to be faced, welded, bond-tested, and autoclave-tested at SRS. This fuel was planned for inclusion in the reactor loads R-9, R-10 (Monthly Report, January 1957), R-11, and R-12 (Monthly Report, February 1957). By July 1957, eight shipping casks containing irradiated thorium fuel had been shipped to ORNL (Monthly Report, July 1957).

In October 1961, Sylcor was authorized to extrude and can 600 hollow thorium metal slugs for use in the Mark IV fuel (Monthly Report, October 1961). In 1962, Bridgeport Brass Company extruded 43,000 kg of thorium metal that was machined and canned at Sylcor. That work resulted in 14,000 Mark VII-T thorium slugs being delivered to SRS for inspection and use in the L-8 Mar VI-B charge (Plant History, 1974, pdf p. 108). Essentially, all of the irradiated thorium fuel was processed off site (usually at ORNL). This work continued sporadically at varying levels of production through 1963.

In 1964, SRS installed vibratory-compaction equipment in 313-M to facilitate the production of thorium oxide (thoria) slugs. Subsequently, the use of off-site vendors was discontinued. [Note: The year 1965 was included in the class period under evaluation to allow time for removal of scrap material.]

Figure 5-1 presents a graphical timeline showing the start-ups of uranium operations, thorium operations, and uranium bioassay.



- (a) Construction History, 1957
 (b) Monthly Report, January 1953; Monthly Report, February 1953; Monthly Report, March 1953
 (c) Monthly Report, January 1954; Monthly Report, February 1954; Monthly Report, March 1954; Monthly Report, April 1954; Monthly Report, May 1954; Monthly Report, June 1954; Monthly Report, July 1954; Monthly Report, August 1954
 (d) Monthly Report, January 1955; Monthly Report, February 1955; Monthly Report, March 1955; Monthly Report, April 1955; Monthly Report, May 1955; Monthly Report, August 1955; Monthly Report, September 1955; Monthly Report, November 1955
 (e) Monthly Report, January 1957; Monthly Report, February 1957; Monthly Report, March 1957; Plant History, 1974
 (f) Health Physics Monthly, Nov. 1953
 (g) Handbook 52, 1953
 (h) Operating Procedure, 1961

Figure 5-1: Start-ups of SRS Uranium Operations, Thorium Operations, and Uranium Bioassay

Only a small number of thorium slugs were handled at SRS compared to the number of uranium slugs. Differences are shown in Table 5-1 for the years 1953 through 1964.

Table 5-1: Uranium vs. Thorium Slugs at SRS				
Year	Number of Uranium Slugs	Number of Thorium Slugs	Thorium Fraction (%)	Notes
1953	200,000	321	0.16	Uranium estimate based partly on 90,109 canned from November 1952 to July 1952.
1954	500,000	1,726	0.36	Thorium canning development work at SRS.
1955	1,200,000	26,618	2.22	Thorium canned at Sylcor Electric Products (SEP) finished at SRS
1956	2,700,000	0	0.00	
1957	751,000	5,200	0.69	Thorium canned at Sylcor Electric Products (SEP) finished at SRS
1958	840,000	0	0.00	---
1959	1,600,000	0	0.00	---
1960	1,106,500	0	0.00	---
1961	725,100	417	0.06	Thorium canned at Sylcor Electric Products (SEP) finished at SRS
1962	955,000	14,000	1.47	Thorium canned at Sylcor Electric Products (SEP) finished at SRS
1963	404,825	16,500	4.08	Thorium canned at Sylcor Electric Products (SEP) finished at SRS
1964	286,900	9,600	3.35	Thorium canned at Sylcor Electric Products (SEP) finished at SRS

6.0 Pedigree of Savannah River Site Data

The following statements apply to the thorium exposure analysis in this evaluation report addendum:

- All air monitoring data used in this analysis came from official SRS primary source documents (i.e., handwritten logs) obtained during NIOSH data captures.
- All bioassay data used in this analysis came from official SRS bioassay record books. Uranium bioassay data recorded in the books through 1965 were entered into spreadsheets for use in the statistical analyses.
- All other documents and data used in this analysis were addressed in the original data pedigree analysis provided in *SEC Petition Evaluation Report for Savannah River Site* (NIOSH, 2008).

7.1 Evaluation of Bounding Internal Radiation Doses at Savannah River Site

ATTRIBUTION: Section 7.1 and its related subsections were completed by Mike Mahathy, Oak Ridge Associated Universities; Sam Chu, Mel Chew and Associates, Inc.; Billy Smith, Mel Chew and Associates, Inc.; and Robert Morris, Mel Chew and Associates, Inc. These conclusions were peer-reviewed by the individuals listed on the cover page. The rationales for all conclusions in this document are explained in the associated text.

In its SRS evaluation report (NIOSH, 2008), NIOSH reserved for future consideration the feasibility determination for thorium exposures from January 1, 1950 through December 31, 1959. Since the publication of the SRS report, NIOSH has evaluated and quantified thorium operations conducted at SRS from 1950 through 1959. During that evaluation, NIOSH determined that the period of thorium metal work for which a common feasibility decision should be applied extended through 1965. This section provides further discussion of thorium operations by year and presents a methodology for bounding potential exposures from thorium metal and thoron. Comparisons of the uranium and thorium processes and data are also provided.

7.1.1.8 Thorium (Th-228, Th-232)

Building 313-M was declared an exclusion area in August 1952; uranium was introduced to the building in September 1952 (Construction History, 1957). The first thorium canning campaign took place in 313-M from January through March 1953, during which about 320 1-kg slugs were canned. In August 1954, Test Authorization Number 3-138, "DPSOX-00530, AlSi Canning Thorium Slugs" in Building 313-M was approved. That authorization identified goals, processes (the same as used for uranium slug canning), responsibilities, and safety controls. The safety controls included: a precaution regarding alpha and gamma radiation; a requirement to use hand and shoe counters; a requirement to run air sampling in thorium-handling areas; an air concentration control limit of $1 \times 10^{-11} \mu\text{Ci}/\text{cm}^3$, at which point respiratory protection would be imposed; and a requirement to cover potentially-contaminated surfaces with paper and dispose of the paper as radioactive waste each day.

By November 1954, four quatrefoil fuel assemblies had been produced and were included in the L-2 reactor loading for irradiation testing (Monthly Report, January 1956; Monthly Report, November 1954). A maximum permissible concentration in air for Th-232 of $2 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$ ($2 \text{ pCi}/\text{m}^3$) was adopted in June 1955 (Health Physics Logbook, 1955).

Early in 1955, SEP was contracted to produce 11,000 hot-press-bonded thorium slugs due to SEP's demonstrated capability for producing uranium slugs using that process as compared to the low yields from the competing AlSi hot-dip process at SRS. The SRS portion of the effort included process research and metallurgy on un-irradiated samples, inspection of the canned slugs and subsequent welding and fabrication into fuel rods. A second order for 15,000 canned thorium slugs was largely fulfilled in August 1955 (Monthly Report, August 1955, pdf pp. 19-20, 32-34). The SEP thorium fuel was used for the R-7¹ full-core reactor loading (Monthly Report, August 1955). In September 1955, the SEP thorium program was reviewed, which resulted in a plan to dispose of the unused inventory by stripping the cans and returning the metal to the Fernald Feed Materials Production Center (FMPC) (Monthly Report, September 1955).

¹ The R-nn and L-nn designations represent the particular reactor and an operating cycle.

In September 1956, SRS received a request to irradiate five tons (~5000 slugs) of thorium to produce U-233 (Monthly Report, September 1956); the plan was to produce material that would then be shipped to ORNL in 0.75-ton batches with minimal cooling time (less than thirty days after discharge) to enable testing of radiation damage to extraction solvents and to determine radiation levels during various stages of the extraction process (Monthly Report, February 1957). Sylcor commenced canning the thorium slugs (Monthly Report, September 1956). About 5,200 canned slugs were to be faced, welded, bond-tested, and tested by autoclave at SRS. The resulting fuel was to be included in reactor loads R-9, R-10 (Monthly Report, January 1957), R-11, and R-12 (Monthly Report, February 1957). By July 1957, eight shipping casks containing irradiated thorium fuel had been shipped to ORNL (Monthly Report, July 1957).

Several SRS reactor loadings included thorium. L-2 included four thorium quatrefoils; R-5 included 252 thorium slugs. Following their 67-day irradiation, these materials were examined for dimensional changes in the 100-R Area Hot Laboratory (Monthly Report, September 1955), then shipped to ORNL in February 1956. R-6 included uranium-thorium quatrefoils (Monthly Report, September 1955) containing 1680 thorium slugs (Monthly Report, January 1956). Those quatrefoils were cooled until January 1956. The R-6 material was shipped to ORNL between January and March 1956 (Monthly Report, January 1956; Monthly Report, February 1956; Monthly Report, March 1956). R-7 was a full thorium load (Monthly Report, August 1955). R-8 included two tubular elements containing enriched uranium and thorium (Monthly Report, November 1955). Loadings R-9, R-10, R-11, and R-12 included material to support testing at ORNL.

In December 1958, ORNL proposed that pellets of mixed 4% enriched UO_2 and ThO_2 be irradiated at SRS. Each pellet was to be 0.26 inches in diameter and 3.5 inches long and was to be clad in stainless steel, aluminum, or Zircalloy (Monthly Report, December 1958). In June 1959, a procedure was tested for making a final arc weld on aluminum-canned hot-press-bonded slugs containing powdered and compacted thorium oxide. Ten slugs were welded and evaluated (Monthly Report, June 1959). The use of a cation resin column to remove thorium in the Plant Special Products process was reported in October 1960, and an analytical procedure for thorium to routinely check column feed and product effluent was evaluated for routine use (Monthly Report, October 1960). In October 1961, irradiated metal waste, including thorium and uranium with 8400 curies of fission products, was shipped from the SRS high-level caves to Building 643-G. The waste was encased in concrete before being shipped to the burial ground (Monthly Report, October 1961).

In October 1961, Sylcor was given authorization to extrude and can 600 hollow thorium metal slugs for use in the Mark IV fuel (Monthly Report, October 1961). The Sylcor cladding process was to be qualified by destructive examination of slugs at SRS. All of the Sylcor pieces were expected for delivery by November 1961 (Monthly Report, October 1961). In 1962, Bridgeport Brass Company extruded 43,000 kg of thorium metal that was machined and canned at Sylcor; this resulted in 14,000 Mark VII-T thorium slugs being delivered to SRS for inspection and use in the L-8 Mar VI-B charge (Plant History, 1974, pdf p. 108).

In February 1963, 6000 Mark VII-T canned thorium slugs were finished at SRS for use in the L-1 charge. In November 1963, 10,500 more thorium slugs were finished for use in the L-2 charge. All 10,500 thorium slugs used in the L-2 charge were examined by radiography (Plant History, 1974, pdf p.116). In 1964, Sylcor made 9600 Mark VII-TS solid thorium metal slugs for two Mark V-E blanket charges but the core quality was reported as poor. Those slugs had been produced from scrap that had

been recycled several times from earlier campaigns (Plant History, 1974, pdf p. 126). Five thorium-enriched uranium alloy tubes clad with zirconium were extruded over April and May 1964 as part of research into developing fuel for the Heavy Water Components Test Reactor (HWCTR) on short notice (Monthly Report, April 1964, pdf p. 184). SRS records show that thorium was transferred within the site in 1964 (Surveys, 1964).

Natural thorium processes at SRS were conducted using the common buildings, equipment, and processing steps used to make natural uranium slugs and were sometimes conducted concurrently. Based on the relative fraction of thorium-to-uranium handled at SRS (as shown in Table 5-1), the mass balance of thorium-to-uranium would have been less than one-to-one. However, the use of a one-to-one mass balance provides for a bounding assumption.

Using Uranium Bioassay as a Substitute for Thorium Bioassay

NIOSH has identified the results of 224 thorium bioassay samples collected in 1956. All results were reported to be less than the detection level limit of 0.5 dpm per 1500 ml sample of urine. NIOSH has discussed the limitations of those thorium bioassay data (NIOSH, 2008). NIOSH has not found additional thorium bioassay for SRS workers. However, NIOSH has obtained the results of uranium urinalyses performed from late 1953 through 1965. As presented in this section of the report, uranium and thorium operational processes were radiologically similar. Therefore, NIOSH intends to use the uranium bioassay as a substitute for thorium bioassay to support its ability to bound thorium internal doses for the time period under evaluation. This substitute data internal dose reconstruction approach is described later in this section.

Area and air monitoring of uranium were performed by the SRS Health Physics group upon start-up. In March 1953, the National Bureau of Standards published *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (Handbook 52, 1953). In Handbook 52, the Subcommittee on Permissible Internal Dose of the National Committee on Radiation Protection (NCRP) stated that all unnecessary exposure to radioisotopes should be avoided but that such avoidance “was often impractical, if not impossible.” Therefore, the subcommittee established levels of maximum permissible exposure to serve as guides to “safe operation and upper levels of exposure.” As a means of detecting levels of uranium exposure, SRS Health Physics implemented a routine uranium bioassay within months of the release of Handbook 52, which is referenced in SRS’s document, *Radiation & Contamination Control* (Operating Procedure, 1961). The SRS Health Physics Monthly Report for September 1953 states that uranium bioassay had been taken for Technical Division staff in Building 678-G, and that a procedure for sampling other areas for uranium urinalysis was worked out with the aid of Methods and Standards and would be put into operation as soon as possible (Health Physics Monthly, Sept. 1953, pdf p. 11). SRS implemented routine bioassay sampling of uranium for 300 Area staff in November 1953 (Health Physics Monthly, Nov. 1953; Health Physics Monthly, Dec. 1953). The first routine samples for uranium were obtained in the 300 Area on November 23, 1953 (Monitoring Log, 1953-1954, pdf p. 22; SRP History, 1954, pdf p. 7). As discussed in Section 7.1.1.8, the routine uranium bioassay program overlapped with thorium operations.

NIOSH evaluated the 1956 SRS thorium bioassay data and limitations of these data in its SRS evaluation report (NIOSH, 2008). NIOSH has not found additional thorium bioassay for SRS workers. NIOSH has obtained all SRS uranium urinalysis data record books (Monitoring Log, 1953-

1954; Uranium Record Book, 1954-55; Uranium Record Book, 1955; Uranium Record Book, 1955-56; Uranium Record Book, 1956a; Uranium Record Book, 1956b; Uranium Record Book, 1956-57; Uranium Record Book, 1957-58; Uranium Record Book, 1959-60; Uranium Record Book, 1960-62; Uranium Record Book, 1962-64; Uranium Record Book, 1964-65).

The data in the record books for workers in the M Area were entered in spreadsheets suitable for statistical analyses. A discussion of the statistical treatment of the uranium record data is provided in Appendix B. The number of workers assigned to M area from 1953 through 1965 is shown in Table 7-1. Also included in this table is the total number of workers used in the statistical analysis, the number of non-censored results, and the number of people monitored as a percentage of the total headcount assigned to the 300 Area. The percentage monitored of the assigned M Area headcount could exceed 100% of the listed workforce due to turnover and because additional workers unassigned to the 300 Area were sometimes brought into the area and monitored.

Table 7-1: M Area Assigned Headcount vs. Bioassay Monitoring Count									
Month	Year	Manufacturing Headcount Assigned to M Area (minus Security personnel)					Bioassay		
		WS	LW	WK	Total		Total Monitored	Non-Censored Results	% Monitored of Assigned Headcount*
December	1953	35	190	---	225		32	32	14.2
June	1954	42	218	---	260		519	514	*199.6
June	1955	80	248	35	363		486	486	*133.9
June	1956	111	449	51	611		722	694	*118.2
May	1957	125	371	49	545		295	45	54.1
June	1958	116	322	44	482		417	92	86.5
June	1959	98	254	36	388		269	70	69.3
May	1960	87	260	38	385		456	58	*118.4
June	1961	92	212	31	335		253	20	75.5
June	1962	83	233	28	344		191	27	55.5
June	1963	77	222	31	330		298	196	90.3
June	1964	75	199	31	305		225	178	73.8
June	1965	62	137	27	226		198	141	87.6

WS = Wilmington Salary wage group

LW = Local Wage group

WK = Weekly wage group

* Values could exceed 100% of the listed workforce due to turnover and because additional workers unassigned to the 300 Area were sometimes brought into the area and monitored.

Feasibility of Bounding Thorium Doses

As stated, NIOSH has a large quantity of uranium bioassay data. NIOSH has demonstrated in this evaluation report addendum that under the conditions of use of natural thorium metal at SRS, these uranium data can be used to support thorium intake modeling. Chronic intakes of natural uranium were modeled using the available uranium data. Annual intakes of Th-232 were derived by assuming a 1:1 mass balance with natural uranium and the specific activities of thorium (Th-232) to natural uranium. Based on the relative fraction of thorium-to-uranium handled at SRS as shown in this report's addendum, the mass balance of thorium-to-uranium would have been less than one-to-one. However, the use of a one-to-one mass balance provides for a bounding assumption.

Using the 50th percentile value of each yearly co-worker uranium excretion rate, daily intake rates of Th-232 were modeled for solubility types M and S and are shown in Table 7-2. The modeling resulted in different daily intake rates for the time periods of 1953, 1954, 1955 through 1956, 1957 through 1962, and 1963 through 1965, respectively. To ensure a bounding assessment, the thorium activity is assumed to be fully-equilibrated among Th-232, Th-228, and Ra-228. Therefore, intake rates of Th-228 and Ra-228 equal to those of Th-232 for each time period for each class were added to the intake model.

Table 7-2: Daily Intake Rates			
Years	Th-232 (pCi/d)	Ra-228 (pCi/d)	Th-228 (pCi/d)
Solubility Type M			
1953	11.1	11.1	11.1
1954	3.73	3.73	3.73
1955-1956	2.69	2.69	2.69
1957-1962	0.16	0.16	0.16
1963-1965	1.18	1.18	1.18
Solubility Type S			
1953	347	347	347
1954	175	175	175
1955-1956	80.4	80.4	80.4
1957-1962	4.77	4.77	4.77
1963-1965	27.0	27.0	27.0

Comparison of Uranium and Thorium Air Sampling Results

SRS records show that the Health Physics organization performed common monitoring steps for uranium and thorium (Air Sample Log Sheets, 1955; Health Physics Logbook, 1955; Shipment Records, 1955; Surveys, 1955a; Surveys, 1955b; Surveys, 1955c; Surveys, 1955d; Surveys, 1956; Surveys, 1962; Surveys, 1963; Surveys, 1964a; Surveys, 1964b; Surveys, 1964c). The same MPC was used for both radionuclides through June 1955 (a maximum permissible concentration for Th-232

of $2 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$ ($2 \text{ pCi}/\text{m}^3$) was adopted in June 1955 [Health Physics Logbook, 1955]). In 1954 and 1955, SRS performed air monitoring for uranium and thorium using the same equipment and procedure. An interview with a former Health Physics Technician on August 13, 2009 (Personal Communication, 2009d) provided insight into the thorium operations. The former Health Physics technician stated:

The routine samples...were representative of the breathing zone of the worker. They were located where the operators were standing and were not mounted on a wall.

Air sample results were recorded on Air Sample Log Sheets. Air sample records were considered workplace monitoring records as opposed to intake monitoring records. Air sample records were associated with each facility separately and were stored as facility records (ORAUT-TKBS-0003, pdf p. 75).

In order to demonstrate how uranium operations compared to thorium operations, NIOSH analyzed air monitoring data obtained from each operation. NIOSH obtained thirty air results for air monitoring of thorium metal operations in 313-M and 320-M in 1954 and 1955 (Air Sample Log Sheets, 1953; Air Sample Log Sheets, 1954a; Air Sample Log Sheets, 1954b; Air Sample Log Sheets, 1955); these are shown in Appendix A, Table A-1. NIOSH selected 33 uranium air sample results from available uranium air monitoring data to test the hypothesis that the mean of the thorium air results was less than or equal to the mean of the uranium results. Uranium air sample results selected for the NIOSH analysis were for air monitoring collected on the same dates, and from the same buildings as the thorium air sample results (Appendix A, Table A-2). The building and location where each sample was collected are included in the table. While uranium and thorium samples were taken in common locations, the distance from the source term sometimes differed. Sampling of uranium processes tended to be from the general work areas (e.g., north of canning line, recovery, process control, and metal labs) so that results would have a slight low bias relative to breathing zone concentrations. Thorium samples were collected closer to the source term, with one sample collected within one foot of the welding head (Air Sample Log Sheets, 1955, pdf p. 59) so that results may be biased high. Sampling was performed using Staplex² high-volume and other vacuum-cleaner-type devices with flow rates ranging from 5.9 to 10.5 ft³/min. Sampling times ranged from thirty to two hundred minutes. Filter papers were used as the collecting media. Air concentrations (pCi/m^3) of total thorium were calculated using the raw data available in the data sheets (gross counts due to counting uncertainties) and assumptions regarding: (1) alpha counting efficiency [30% under 2 • geometry for a calibration source³]; (2) particle collection efficiency of the sampling media (95%³) and (3) sample self-absorption (50%³). Th-232 was assumed to be in equilibrium with Th-228 and Ra-228; therefore, concentrations of total thorium were divided by 3 to obtain the concentrations of Th-232. Th-232 mass concentrations were derived using a specific activity of 0.111 pCi/ μg ; uranium mass concentrations were derived using a specific activity of 0.672 pCi/ μg . The mass concentrations ($\mu\text{g}/\text{m}^3$) for Th-232 and natural uranium are included in Appendix A, Tables A-1 and A-2 respectively.

² Attribution: Bryce Rich, Mel Chew and Associates, Inc.

³ Attribution: Robert Morris, Mel Chew and Associates, Inc. These assumptions are based on extensive experience with alpha counter and air sampling equipment. Several of these assumptions can be substantiated in the Air Force Institute of Operational Health consultative letter, *Alpha Correction Factor for New Bioenvironmental Engineering Radiological Air Sampling Equipment – RAdECo® Model H-809VII* (Correction Factor, 2005).

Descriptive statistics were generated for the thorium dataset and the uranium dataset using mass concentrations; these are shown in Table 7-3.

Table 7-3: Description Statistics for SRS Thorium and Uranium Data		
Statistic	Th-232	Uranium
number of samples	30	33
minimum ($\mu\text{g}/\text{m}^3$)	0.49	0.35
first quartile ($\mu\text{g}/\text{m}^3$)	2.02	2.29
mean ($\mu\text{g}/\text{m}^3$)	6.40	4.48
median ($\mu\text{g}/\text{m}^3$)	3.86	4.71
standard deviation	6.17	3.10
third quartile ($\mu\text{g}/\text{m}^3$)	8.22	6.26
maximum ($\mu\text{g}/\text{m}^3$)	25.5	16.21
geometric mean ($\mu\text{g}/\text{m}^3$)	4.00	3.36

The descriptive statistics were used to generate the box-and-whisker plots in Figure 7-1. When two box-and-whisker plots are displayed on the same scale, as in Figure 7-1, key features of the data can be graphically compared. The minimum values of both distributions are as close to zero as can be measured with the selected technology. The box portion of the plot is bounded by the lower quartile and upper quartile values and the median is between those two values (represented by the horizontal solid line inside the box). The box defines the range of the middle 50% of the data, which is also called the interquartile distance. Whiskers on each side of the box represent the 10th and 90th percentiles; the black dots represent the 5th and 95th percentiles. The conclusion drawn from this figure is that the thorium distribution median values are generally less than the uranium distribution. Thus, the plots support the hypothesis that the thorium concentrations are in the same airborne concentration range (by mass) as the uranium values and the internal exposure profiles for uranium and thorium are similar.

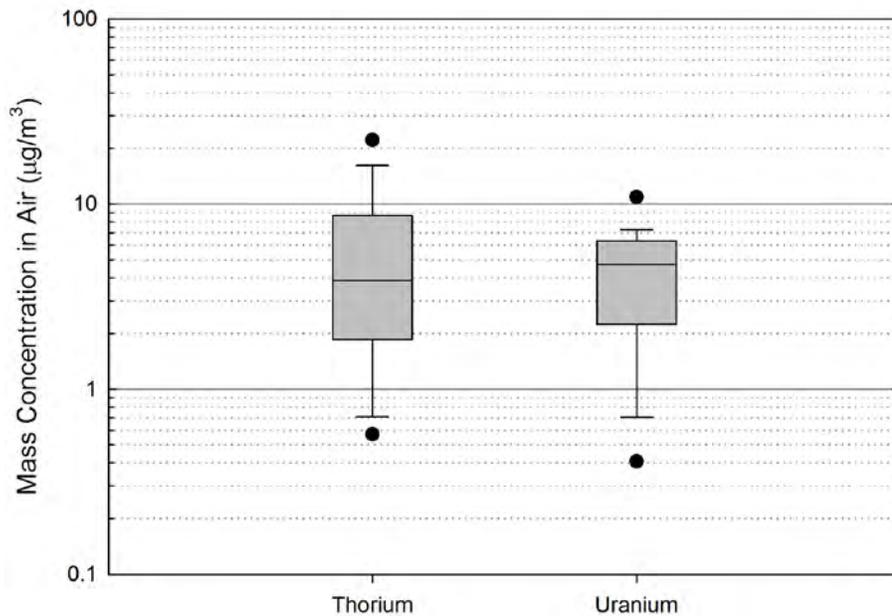


Figure 7-1: Comparison of SRS Thorium and Uranium Air Sample Data

NIOSH performed a one-tail t-Test analysis (two-sample assuming unequal variances) to test the hypothesis that the mean of the natural log of the mass concentrations of thorium was less than or equal to the mean of the natural log of the mass concentrations obtained for uranium using $\alpha = 0.05$ ($H_0 : \mu_t = \mu_u$) with the alternate hypothesis $H_1 : \mu_t > \mu_u$. In order for the hypothesis to be true, $t > t_{critical}$ must be true. Results of the hypothesis test are shown in Table 7-4.

Table 7-4: t-Test Analysis		
(Data values used in the analysis are log transformations of the mass concentrations)		
	Thorium	Uranium
mean	1.39	1.21
variance	1.11	0.78
observations	30	33
hypothesized mean difference	0	---
degrees of freedom	57	---
α	0.05	---
t	0.717	---
p value one-tail	0.238	---
t-critical one-tail	2.00	---

With a p value of 0.238, there is not sufficient statistical evidence to reject the null hypothesis ($\mu_t = \mu_u$) in favor of the alternate hypothesis ($\mu_t > \mu_u$).

Plausibility of Intakes Derived Using Uranium Bioassay

In order to check the plausibility of intakes derived using the uranium urinalysis data, NIOSH estimated intakes of thorium using: (1) the air monitoring data displayed in Appendix A, Table A-1; and (2) the 1956 thorium bioassay data (NIOSH, 2008).

Thorium intake rates were estimated using the air monitoring data provided in Appendix A, Table A-1. The geometric mean of the thorium air concentrations by mass was $6.4 \mu\text{g}/\text{m}^3$, which equals $0.715 \text{ pCi}/\text{m}^3$ using the specific activity for Th-232 of $0.111 \text{ pCi}/\mu\text{g}$. The geometric mean of $0.715 \text{ pCi}/\text{m}^3$ is less than the 1954 Th-232 MPC of $10 \text{ pCi}/\text{m}^3$ and less than the Th-232 MPC of $2 \text{ pCi}/\text{m}^3$ in use from 1956 through 1965. Therefore, NIOSH used an air concentration for Th-232 of $2 \text{ pCi}/\text{m}^3$ (the latter MPC) to derive a comparative intake rate. Using a breathing rate of $1.2 \text{ m}^3/\text{hr}$ applied over an 8-hour work day yields a daily intake of 19.2 pCi (Type S material assumed). The intake rate is on the same order of magnitude as the average daily intake rate obtained using the uranium bioassay data, which supports the use of those substitute data.

All thorium bioassay data for 1956 were reported as less than the Th-232 detection limit of 0.5 dpm per 1500 mL. Therefore, NIOSH estimated chronic inhalation using the Th-232 detection limit and evaluated the result. The resulting annual inhalation intake rate of 650 pCi per day was derived; that rate was assumed to be constant through 1965. Although this value is higher than the intake rates using the uranium data, such an intake rate would equate to a constant air concentration for Th-232 of $34 \text{ pCi}/\text{m}^3$ which is significantly higher than the Th-232 maximum permissible concentration averaged over the entire span of time from 1953 through 1965. Given this information, NIOSH does not find that employing the Th-232 limit of detection provides a plausible analysis of potential thorium intakes in light of the available air sampling data and the known rates of thorium metal processing.

Bounding of Doses from Intakes of Thoron

Exposures to radon-220 (thoron) and its short-lived progeny cannot be discounted during the time period when thorium metal was processed at SRS (1953-1965). NIOSH has found no air sampling collected to measure concentrations of thoron. However, applying conservative assumptions, NIOSH used data from Appendix A, Table A-1, where samples were counted at least twice, to estimate an upper bound for thoron air concentration. The extrapolation from long-lived air sample data to thoron concentration in air was made using the following assumptions:

- The Pb-212 half-life of 10.64 hours was used to extrapolate the initial airborne alpha count rate between sample collection and the first count.
- The filter paper contained both long-lived activity and short-lived activity.
- The build-up of thoron on the filter paper during sampling should be approximated.
- The decay that occurred between the end of the sampling and the first count should be calculated.

Using the methodology described in Appendix C, the thoron concentrations were derived and are shown in Table 7-5. Intakes in pCi/day of thoron were calculated by assuming a breathing rate of 1.2 m³/hour for 8 hours, and using an overall counting and collection efficiency of 0.29.

Table 7-5: Results of SRS Thoron Assessment							
Date	Total Sample Collection Time (hrs)	Time Between Collection and Start of First Count (hrs)	Initial cpm	Decayed cpm	Hours After First Count Until Decayed Count	Flow Rate (ft ³ /min)	Thoron pCi/m ³
4/15/55	1.00	5.58	29.8	3.8	67.00	7.9	4.56
7/9/54	1.92	4.00	182.6	8.0	72.00	7.9	16.8
7/9/54	1.67	4.25	108.5	26.1	72.00	7.9	8.06
7/30/54	1.58	0.33	214.3	28.0	67.00	7.9	14.8
6/29/54	1.92	4.08	76.9	44.0	8.67	7.9	10.7
7/8/54	1.00	4.48	120.0	37.3	24.00	7.9	18.4
7/7/54	1.00	4.10	128.7	55.3	24.50	7.9	15.8
5/3/55	1.00	1.07	256.7	12.9	24.00	10.5	30.4

The concentrations were fit to a lognormal distribution with the following parameters: GM = 13.1 pCi/ m³; GSD = 1.78; arithmetic mean = 14.9 pCi/m³; and 95th percentile = 26.2 pCi/ m³. The daily intake of thoron is bounded by the product of the geometric mean (13.1 pCi/ m³) with the breathing rate of 9.6 m³ of air per 8-hour work shift which gives 126 pCi.

7.4.5 Bounding of Doses from Intake of Thorium

NIOSH has established in Section 7.1.1.8 that internal doses resulting from potential exposures to thorium can be plausibly bounded for SRS construction workers using uranium bioassay as a substitute data set.

7.5 Summary of Feasibility Findings for Petition SEC-00103

This addendum to the Savannah River Site Evaluation Report (SEC-00103) evaluates the feasibility of estimating with sufficient accuracy the dose received from potential exposures to thorium for all construction workers who worked in any area at the Savannah River Site during the period from January 1, 1953 through December 31, 1965.

NIOSH determined that it has sufficient personal monitoring data, source term information, and workplace monitoring data for thorium to allow adequate bounding of the total potential internal exposures at the site during this time period. Consequently, NIOSH finds that it is feasible to estimate with sufficient accuracy the radiation doses resulting from internal thorium exposures received by members of this class.

NIOSH has documented herein that it can complete the dose reconstructions related to this addendum (i.e., doses resulting from exposure to thorium from January 1, 1953 through December 31, 1965). The basis of this finding is specified in this addendum, which demonstrates that NIOSH has access to sufficient information to estimate with sufficient accuracy either the maximum radiation dose incurred by any member of the class or to estimate such radiation doses more precisely than a maximum dose estimate.

NIOSH has documented in its original SEC-00103 Evaluation Report (NIOSH, 2008), and in this addendum, that it can complete dose reconstructions for exposure to all site occupational radiation sources for all construction workers who worked in any area at the Savannah River Site during the time period from January 1, 1950 through December 31, 2007.

Note: An Appendix follows the References section.

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Appendix A

Table A-1: SRS Thorium Samples							
Sampled for	Building	Location	Comment	Collection Date	cpm	Derived Concentration Th-232 (pCi/m ³)	Mass/volume Th-232 (µg/m ³) [†]
thorium	320M	Lathe Room	Cutting and machining rods	6/22/1954	14.3	0.37	3.37
thorium	320M	Lathe Room	Cutting and machining rods	6/22/1954	12.0	0.30	2.74
thorium	320M	Lathe Room	Cutting and machining rods	6/23/1954	28.0	0.69	6.26
thorium	320M	Lathe Room	Cutting and machining rods	6/23/1954	56.7	1.34	12.03
thorium	320M	Lathe Room	Cutting and machining rods	6/25/1954	4.0	0.07	0.64
thorium	320M	Lathe Room	Cutting and machining rods	6/25/1954	7.7	0.16	1.41
thorium	320M	Lathe Room	Cutting and machining rods	6/25/1954	36.3	0.47	4.28
thorium	320M	Lathe Room	Cutting and machining rods	6/28/1954	31.0	0.37	3.29
thorium	320M	Lathe Room	Cutting and machining rods	6/29/1954	44.0	0.90	8.12
thorium	320M	Lathe Room	Cutting and machining rods	6/29/1954	42.8	0.92	8.25
thorium	320M	Lathe Room	Cutting and machining rods	6/29/1954	38.3	0.62	5.60
thorium	320M	Lathe Room	Cutting and machining rods	6/30/1954	35.0	0.78	7.07
thorium	320M	Lathe Room	Cutting and machining rods	6/30/1954	30.0	2.83	25.46
thorium	320M	Lathe Room	Cutting and machining rods	7/1/1954	10.0	0.26	2.36
thorium	320M	Lathe Room	Cutting and machining rods	7/2/1954	4.7	0.10	0.87
thorium	320M	Lathe Room	Cutting and machining rods	7/2/1954	3.7	0.32	2.88
thorium	320M	Lathe Room	Cutting and machining rods	7/6/1954	46.6	1.83	16.48
thorium	320M	Lathe Room	Cutting and machining rods	7/7/1954	55.3	2.17	19.55
thorium	320M	Lathe Room	Cutting and machining rods	7/8/1954	37.3	1.46	13.19
thorium	320M	Lathe Room	Cutting and machining rods	7/9/1954	8.0	0.19	1.70
thorium	320M	Lathe Room	Cutting and machining rods	7/9/1954	26.1	0.61	5.54
thorium	320M	Spectro-Chem Lab	Grinding	7/30/1954	28.0	1.10	9.90

Table A-1: SRS Thorium Samples							
Sampled for	Building	Location	Comment	Collection Date	cpm	Derived Concentration Th-232 (pCi/m ³)	Mass/volume Th-232 (µg/m ³) [†]
thorium	320M	Swagging Area	Swagging of rods	8/11/1954	9.0	0.21	1.91
thorium	320M	Swagging Area	Swagging of rods	8/12/1954	3.0	0.05	0.49
thorium	313M	North of Canning Line	Normal Operation	8/30/1954	28.9	0.73	6.60
thorium	313M	North of Canning Line	Canning Slugs	12/22/1954	70.0	1.46	13.15
thorium	313M	Special Process	Handling Thorium	4/15/1955	3.8	0.15	1.34
thorium	313M	Special Process	One foot from welding of slugs	4/15/1955	2.6	0.08	0.69
thorium	313M	Special Process	Two feet from welding of slugs	4/15/1955	3.6	0.38	3.41
thorium	313M	Special Process	Thorium in room	5/3/1955	12.9	0.38	3.43

[†] Thorium mass based on specific activity of Th-232.

Table A-2: SRS Uranium Samples							
Sampled for	Building	Location	Comment	Collection Date	cpm	Derived Concentration U-nat (pCi/m ³)	Mass/volume U-nat (µg/m ³) [†]
uranium	320M	Process Control	Normal operation	6/22/1954	29.3	4.30	6.40
uranium	320M	Metal Labs	Normal operation	6/23/1954	27.6	2.37	3.53
uranium	320M	Process Control	Normal operation	6/29/1954	26.7	3.31	4.93
uranium	320M	Metal Labs	Normal operation	6/30/1954	27.5	3.41	5.08
uranium	320M	Metal Polishing Lab	Cutting and polishing metal	7/8/1954	28.0	2.60	3.88
uranium	320M	Metal Labs	Normal operation	7/28/1954	25.0	4.65	6.92
uranium	320M	Metal Labs	Normal operation	7/28/1954	27.0	4.31	6.41
uranium	320M	Spectro-Chem Lab	Grinding	8/3/1954	33.0	2.22	3.30
uranium	320M	Metal Labs	Normal operation	8/4/1954	28.9	3.58	5.33
uranium	320M	Metal Labs	Unusual amount of slugs	8/10/1954	25.1	4.67	6.95
uranium	320M	Process Control	Normal operation	8/10/1954	27.0	5.02	7.47
uranium	320M	Process Control	Normal operation	8/17/1954	25.6	4.08	6.07
uranium	320M	Metal Labs	Normal operation	8/18/1954	26.4	4.21	6.26
uranium	313M	Recovery	---	8/30/1954	27.9	2.16	3.22
uranium	313M	Storage	Normal operation	8/30/1954	33.6	3.17	4.71
uranium	313M	North of Canning Line	Normal operation	8/30/1954	40.7	3.83	5.71
uranium	313M	Lathe Room	Stripping from cans	8/30/1954	114.2	10.9	16.29
uranium	313M	Recovery	Normal operation; some spillage	8/30/1954	32.9	1.77	2.64
uranium	313M	North of Canning Line	Normal operation	12/22/1954	44.8	3.18	4.72
uranium	313M	North of Canning Line	Normal operation	12/22/1954	33.6	3.17	4.71

Table A-2: SRS Uranium Samples							
Sampled for	Building	Location	Comment	Collection Date	cpm	Derived Concentration U-nat (pCi/m ³)	Mass/volume U-nat (µg/m ³) [†]
uranium	313M	Final Storage	Cleaning canned Slugs	12/22/1954	20.8	1.47	2.19
uranium	313M	Recovery	Cleaning	12/22/1954	61.6	5.80	8.64
uranium	313M	X-ray	Normal operation	12/22/1954	49.6	4.67	6.95
uranium	313M	Cleaning	Cleaning	4/15/1955	12.1	1.14	1.70
uranium	313M	North of Canning Line	Normal operation	4/15/1955	9.4	0.89	1.32
uranium	313M	Recovery	Normal operation	4/15/1955	21.7	1.54	2.29
uranium	313M	Recovery	Normal operation	4/15/1955	31.0	2.20	3.27
uranium	313M	North of Canning Line	Normal operation	4/15/1955	31.0	2.20	3.27
uranium	313M	North of Canning Line	Normal operation	5/3/1955	6.1	0.57	0.86
uranium	313M	Recovery	Cleaning	5/3/1955	3.3	0.23	0.35
uranium	313M	South of Canning Line	Normal operation	5/3/1955	14.2	1.01	1.50
uranium	313M	North of Canning Line	Normal operation	5/3/1955	4.3	0.41	0.60
uranium	313M	Recovery	Normal operation	5/3/1955	4.1	0.29	0.43

[†] Uranium mass based on specific activity of natural uranium.

Appendix B

The SRS uranium-mass-in-urine data from the logbooks were supplied in an Excel file. The worksheet was converted to a comma separated value (csv) file and read into the R analysis tool. The uranium concentration in each urine sample was calculated from the fluorimetry results using the following equation (Uranium Record Book, 1954-55):

$$U = 250 \frac{R}{R_s - R},$$

Where:

- U = Concentration of uranium in urine ($\mu\text{g/L}$)
- R = Mean of three fluorimetry readings from the sample
- R_s = Mean of two fluorimetry readings from a known spike

The concentration U calculated above was used for the co-worker models unless the fluorimetry readings were missing or the concentration was equal to zero. If the fluorimetry readings were missing, the reported concentration (which may have been censored) was used. If U was equal to zero the result was censored, with the censoring level (CL in the plots) being set equal to the minimum non-zero concentration reported for that year.

All uranium-in-urine concentrations were converted to $\mu\text{g}/1.5 \text{ L}$, grouped by year, and the highest result for each individual in a given year was selected. The urine data for 1953 through 1956 were satisfactorily fit with a single lognormal distribution using a maximum likelihood method (the data had multiple censoring levels so a regression on the order statistics could not be done).

The parameters given in the plots for 1953-1956 include the geometric mean (GM), geometric standard deviation (GSD), total number of results (N), number of uncensored results (n), and the coefficient of determination (R^2). For this application, R^2 is defined to be the square of the correlation coefficient between the log observed uncensored data y and the log predicted uncensored data \hat{y} :

$$R^2 = [\text{cor}(\ln(y), \ln(\hat{y}))]^2$$

For a linear relationship such as the line of best fit in the plots, this definition of R^2 is numerically equal to the standard definition for R^2 :

$$R^2 = 1 - \frac{\sum(y - \hat{y})^2}{\sum(y - \bar{y})^2}$$

Statistics derived using these methods are summarized in Table B-1.

Table B-1: Derived Statistics Used for Intake Modeling			
Year	GM	GSD	84th
1953	5.557	1.386	7.70
1954	2.805	1.847	5.18
1955	1.97	1.724	3.40
1956	1.555	1.698	2.64
1957	0.152	3.01	0.46
1958	0.185	3.49	0.65
1959	0.205	3.77	0.77
1960	0.146	2.92	0.43
1961	0.127	2.51	0.32
1962	0.169	3.43	0.58
1963	0.559	4.19	2.34
1964	0.923	3.57	3.30
1965	0.571	3.77	2.15

Figure B-1 shows a box-and-whisker plot depicting the change in fitted uranium urine concentration over time. The lower and upper dots for each year represent the 5th and 95th percentiles, while the lower and upper whiskers represent the 10th and 90th percentiles. The traditional box represents the inner 50th percentile; thus, the lower limit of the box is equal to the 25th percentile while the upper portion represents the 75th percentile. The solid line in the middle of the box represents the 50th percentile or the geometric mean of the fitted uranium urine concentration whereas the dotted line is the arithmetic mean. This figure illustrates that from 1953 through 1957, there was a steady decrease in the uranium urine concentration among workers in the 300 Area. From 1957 through 1962, the urine concentration remained relatively low with a geometric mean typically less than 0.2 ug/d. From 1963 through 1965, there was an increase in the urine concentration among the 300 Area workers.

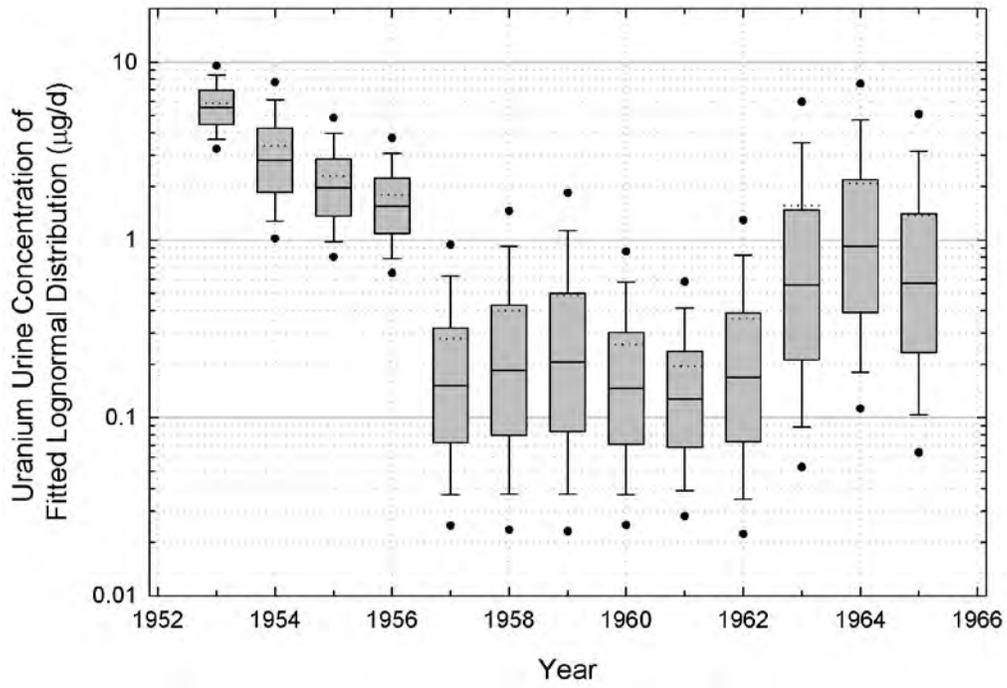


Figure B-1: Derived Statistics Used for Intake Modeling

Plots for each of the years 1953 through 1965 are presented in Figures B-2 through B-14.

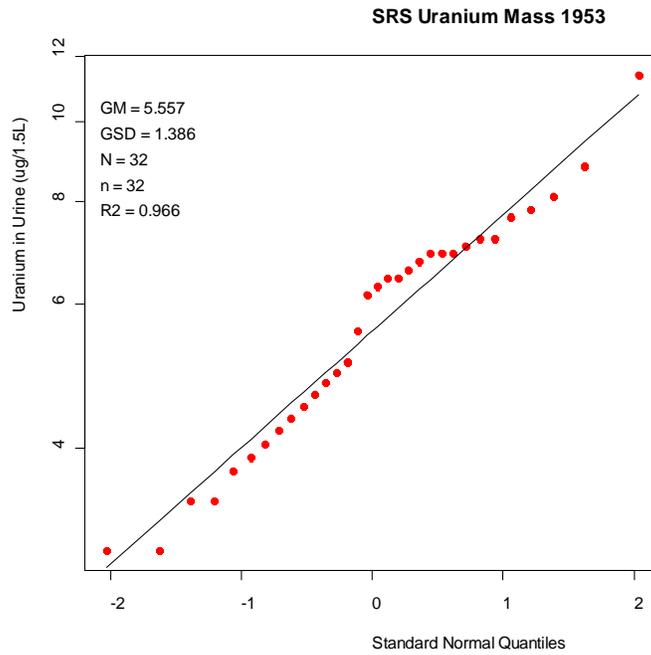


Figure B-2: SRS Uranium Mass Statistical Fit for 1953

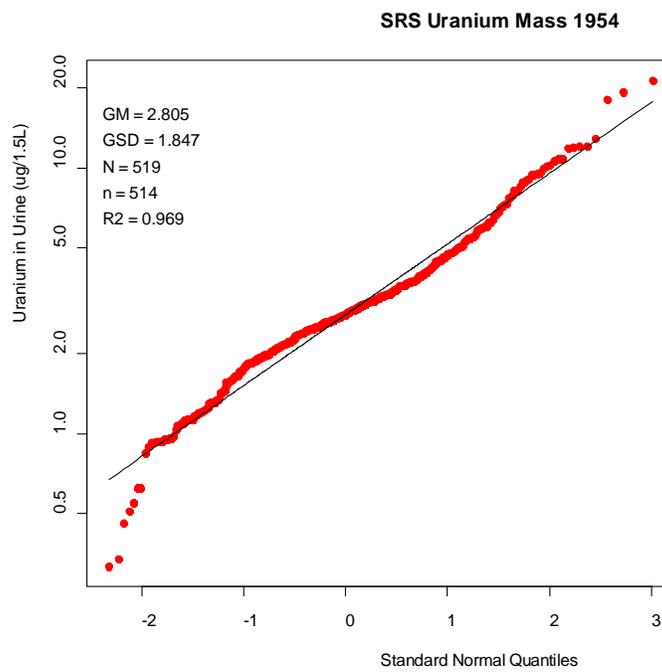


Figure B-3: SRS Uranium Mass Statistical Fit for 1954

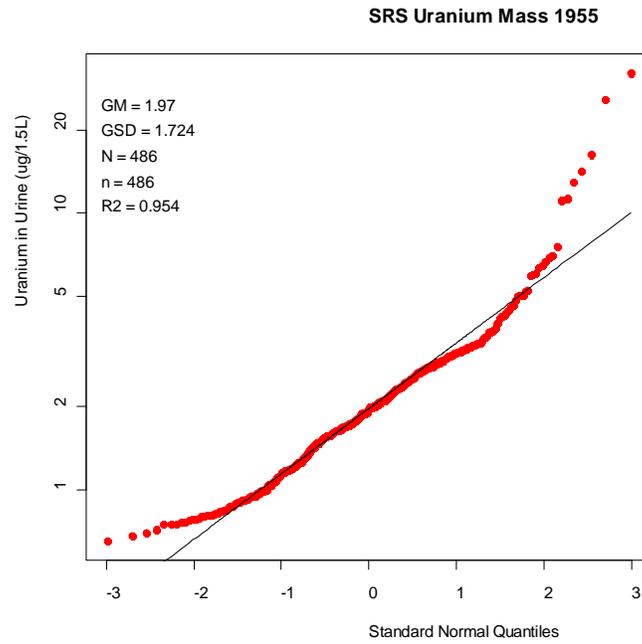


Figure B-4: SRS Uranium Mass Statistical Fit for 1955

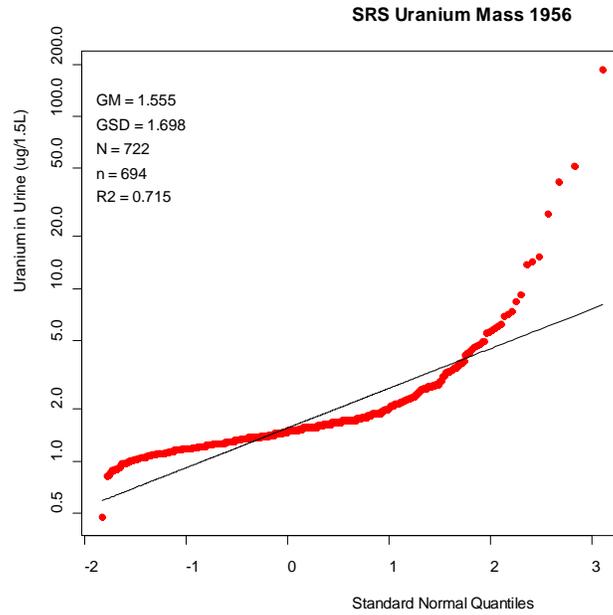
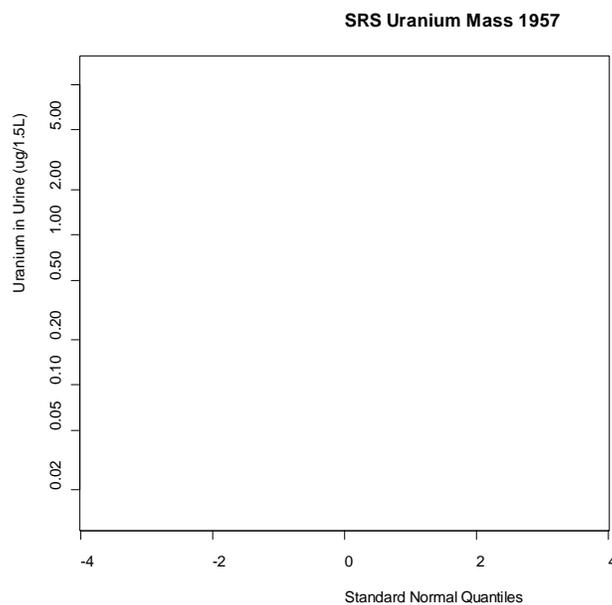
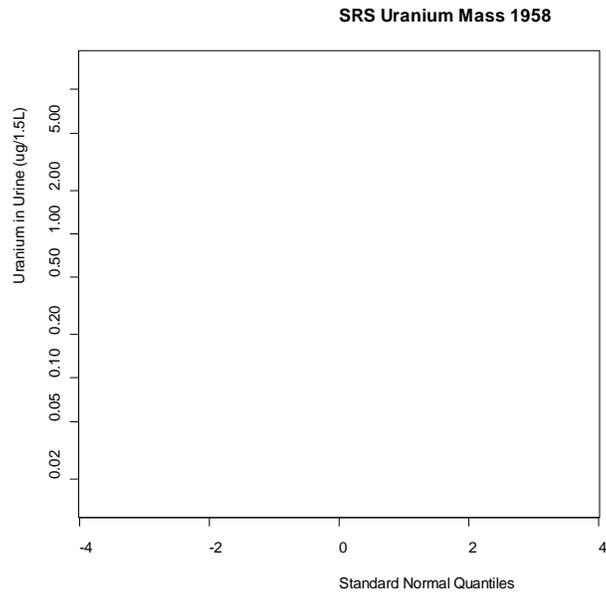


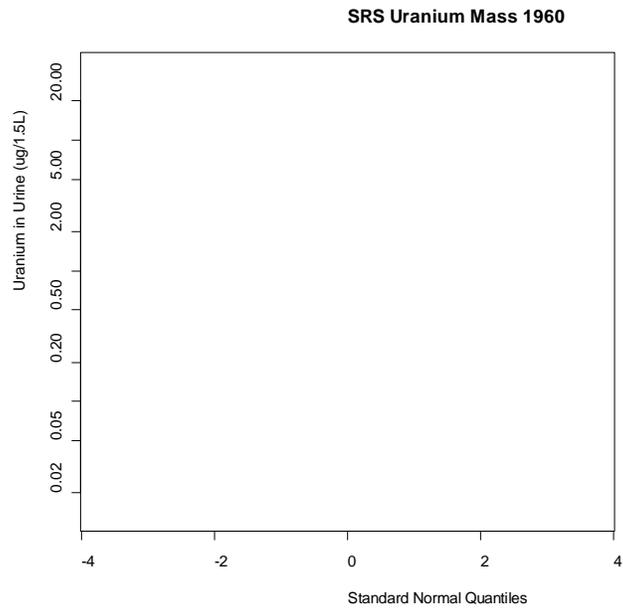
Figure B-5: SRS Uranium Mass Statistical Fit for 1956

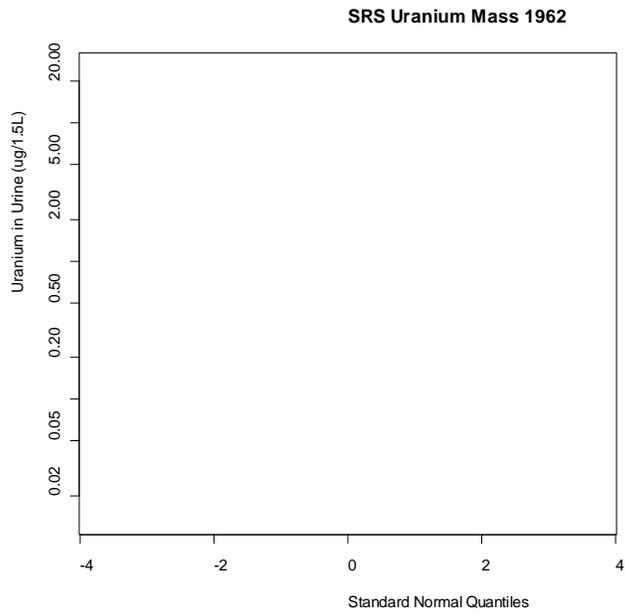
For the years 1957-1965, the data were fit with a sum of two lognormal distributions using the maximum likelihood methods described in ORAUT-RPRT-0044 to give an effective fit to the data. Note that the analytical background for the uranium urine data is lognormal rather than normal as described in ORAUT-RPRT-0044. The geometric mean and geometric standard deviation of the lognormal distribution below the censoring level (i.e., the analytical background) was selected to give the highest coefficient of determination (R^2) for the fit to the uncensored data. Using this criterion, a GM value of 0.1 and a GSD value of 1.75 were selected for the analytical background for 1957-1965.

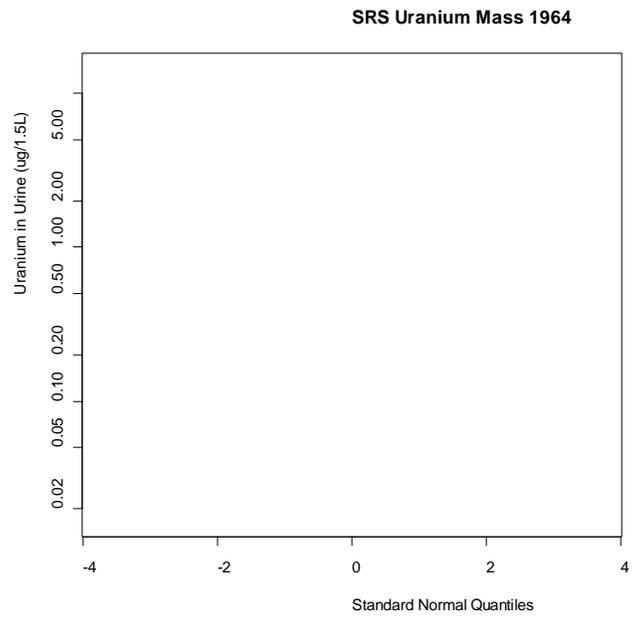
Given the above analytical background, the GM and GSD for the “exposed” distribution are calculated along with the fraction of the population estimated to be analytical background. For example, for the exposed distribution in 1957 the GM = 2.54 and the GSD = 1.68. The fraction of the population that comprises analytical background is 0.8699, which means that the exposed fraction makes up $1 - 0.8699 = 0.1301$ of the population. The dashed line in the plot is the best fit to the data using the two lognormal distributions. The sigmoid-shape of the curve is a result of plotting two independent distributions on the same probability plot. The “effective” fit to the data is a single lognormal distribution (GM=0.152, GSD=3.01) represented by the solid line. The GM and GSD from the effective fit are used in the co-worker model.











The statistical parameters given in Table B-1 were used to model the daily intake rate of natural uranium. The modeled data resulted in different daily intake rates for the time periods of 1953, 1954, 1955 through 1956, 1957 through 1962, and 1963 through 1965, respectively. To obtain daily intake rates of Th-232, a mass balance of one-to-one of natural uranium to Th-232 was assumed, giving the same mass intake rate for each year. To ensure a bounding assessment, the thorium activity is assumed to be fully-equilibrated among Th-232, Th-228, and Ra-228. Therefore, intake rates of Th-228 and Ra-228 equal to those of Th-232 were added to the intake model for each time period for each class. Derived intake rates are given in Table B-2.

Table B-2: Thorium, Daily Intake Rates							
Years	U (pCi/day)	U:Th Mass Ratio	Th-232: Ra-228 Activity Ratio	Th-232: Th-228 Activity Ratio	Th-232 (pCi/day)	Ra-228 (pCi/day)	Th-228 (pCi/day)
Type M							
1953	67.1	1	1	1	11.1	11.1	11.1
1954	22.6	1	1	1	3.73	3.73	3.73
1955-1956	16.3	1	1	1	2.69	2.69	2.69
1957-1962	0.97	1	1	1	0.16	0.16	0.16
1963-1965	7.15	1	1	1	1.18	1.18	1.18
Type S							
1953	2100	1	---	1	347	347	347
1954	1060	1	---	1	175	175	175
1955-1956	487	1	---	1	80.4	80.4	80.4
1957-1962	28.9	1	---	1	4.77	4.77	4.77
1963-1965	163	1	---	1	27.0	27.0	27.0

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Appendix C

The thoron concentrations in Table 7-5 were calculated using the following methodology.

$$\begin{aligned} A1 &= AL + AT1 \\ A2 &= AL + AT2 \\ AT2 &= AT1 e^{(-\lambda * T2)} \end{aligned}$$

Where:

- A1 and A2 = Filter activity during the first and second count
- AL = Long-lived activity on the filter paper
- AT1 and AT2 = Thoron activity on the filter during the first and second count
- ATF = Thoron activity on the filter paper at the end of the sampling
- TS = Sample time (time the sample ran)
- T1 = Time between the end of sampling and the first count
- T2 = Time between the first and second counts
- λ = Pb-212 λ = (ln(2)/10.64 hours)

Step 1:

Solve these three equations for AT1 as follows:

$$AT1 = (A1 - A2) / (1 - e^{(-\lambda * T2)})$$

Since AT1 is the thoron activity on the filter paper during the first count, it must now be corrected for the decay that occurred between the end of the sampling and the first count.

$$ATF = AT1 * e^{(\lambda * T1)}$$

(Note: this is a positive exponent)

Step 2:

To arrive at the concentration of thoron in the air, the build-up of thoron on the filter during sampling must be considered. This can be expressed as:

$$ATF = CT * R / \lambda * (1 - e^{(-\lambda * TS)})$$

Where:

- CT = Thoron concentration in the air
- R = Sampling rate (volume per time)

This can be rearranged to:

$$CT = ATF * \lambda / R / (1 - e^{(-\lambda * TS)})$$

Combining this with the previous equations gives:

$$CT = [\underline{\{(A1 - A2) / (1 - e^{(-\lambda * T2)})\}} * e^{(\lambda * T1)}] * \lambda / R * \{1 / (1 - e^{(-\lambda * TS)})\}$$

The underlined part represents ATF (Step 1) and the remainder is the build-up correction.