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Internal Dosimetry Co-Exposure Data for Oak Ridge National Laboratory

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Subject Expert(s): Matthew G. Arno

Document Owner Approval:	Signature on File Matthew G. Arno, Document Owner	Approval Date:	03/30/2020
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	04/01/2020
Concurrence:	Signature on File Scott R. Siebert, Objective 3 Manager	Concurrence Date:	03/30/2020
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	03/30/2020
Approval:	Signature on File Timothy D. Taulbee, Associate Director for Science	Approval Date:	08/05/2020

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
12/13/2005	00	New technical information bulletin for assignment of X-10 internal doses based on coworker bioassay data. First approved issue. Training required: As determined by the Task Manager. Initiated by William E. Kennedy, Jr.
04/23/2013	01	Plutonium modeling updated to include best estimate intakes for type S material. 95th-percentile intakes added for all nuclides. Attachment A data tables expanded to include information on the number of samples and employees used in the statistical analysis. Incorporates formal internal review comments. No changes occurred as a result of formal NIOSH review. Training required: As determined by the Objective Manager. Initiated by Matthew G. Arno.
01/21/2014	02	Revision to modify Sections 4.3.5, 5.1, and 5.2 to reference OTIB-0054 rather than provide fission products ratios based on environmental monitoring records. Clarification added that type S strontium should only be applied if exposure to strontium titanate is assumed. In addition, guidance on when to assign the 95th-percentile intake rates was added. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Matthew G. Arno.
05/05/2014	03	Revision initiated to remove the inclusion of the Pilot Plant in Section 4.3.5 and Section 5.2, first bullet. Updated references. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Matthew G. Arno.
09/01/2020	04	Revision initiated to include adding the potential and intake rates for type SS plutonium. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Matthew G. Arno.

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ACRONYMS AND ABBREVIATIONS

CER	Center for Epidemiologic Research
d	day
DOE	U.S. Department of Energy
dpm	disintegrations per minute
EDP	Electronic Data Processing
F	fast (absorption type)
GM	geometric mean
GSD	geometric standard deviation
hr	hour
ICRP	International Commission on Radiological Protection
IDOT	Internal Dosimetry Tool
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
m	meter
M	moderate (absorption type)
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
ORISE	Oak Ridge Institute for Science and Education
ORNL	Oak Ridge National Laboratory
S	slow (absorption type)
SRDB Ref ID	Site Research Database Reference Identification (number)
SS	super slow (absorption type)
TIB	technical information bulletin
USC	*United States Code*
µm	micrometer

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document, the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy (DOE) facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 *United States Code* (USC) 7384l(5) and (12)].

2.0 PURPOSE

There are instances of energy employees who, for a variety of reasons, were not monitored for internal exposure during the course of their employment at a DOE facility, or for whom records of such monitoring are incomplete or unavailable. In these cases, monitoring data from other workers with similar exposure potential can be used to approximate another individual's possible exposure using a co-exposure study. The purpose of this TIB is to provide the details of the calculation and assignment of co-exposure intakes based on data from workers with similar exposure potential from Oak Ridge National Laboratory (ORNL, formerly known as X-10) for estimation of unmonitored exposures or if records of monitoring are incomplete or unavailable, whether for discrete periods or for the entire period of employment.

3.0 OVERVIEW

ORAUT-OTIB-0019, *Analysis of Coworker Bioassay Data for Internal Dose Assignment*, describes the general process used for analyzing bioassay data for assigning doses to individuals based on results from workers with similar exposure potential [ORAUT 2005].

Bioassay results for ORNL were obtained from the Oak Ridge Institute for Science and Education (ORISE) Center for Epidemiologic Research (CER) Dosimetry Database, which contains urinalysis records from the ORNL site for 1951 to 1988. ORISE obtained this database from ORNL to conduct an epidemiology study of site workers. The database results are in units of disintegrations per minute per 24 hours. Because of the varied operations at the different ORNL facilities over time, the database contains urinalysis data for numerous radionuclides. These data are stored using Electronic Data Processing (EDP) codes, as documented in Section 5.2.4.2 of ORAUT-TKBS-0012-5, *Oak Ridge National Laboratory – Occupational Internal Dose* [ORAUT 2013].

In summary, data were stored under 64 EDP codes and included measurements for five radioisotopes of uranium, four radioisotopes of plutonium, seven other transuranic radionuclides, numerous fission and activation products, and gross alpha and gross beta measurements. The majority of the EDP codes contained fewer than 100 data entries. In reviewing these data, it was determined that only a few EDP codes contained enough entries to allow statistical evaluation for dose reconstruction. These were:

- SR and SR0 for ^{90}Sr (12,893 entries from 1951 to 1988);
- UR0 and UR for total uranium (11,434 entries from 1951 to 1988);
- PU0, PU9, PU, GA0, and GU0 for plutonium alpha emitters (15,476 entries from 1951 to 1988); and

- TP0 and TP for transplutonium radionuclides, primarily ^{241}Am (5,670 entries from 1968 to 1987).

GA0 and GU0 (gross alpha) results are treated as plutonium results as indicated in Table 5-6 of ORAUT [2013]. Transplutonium radionuclides were assumed to be and modeled as ^{241}Am for this co-exposure study.

Further review of these data indicated that, except for followup for accidental exposures, they were collected on an annual sampling basis; therefore, the analysis that follows considers chronic exposures to estimate annual intakes. A statistical analysis of these data was performed in accordance with ORAUT-OTIB-0019 [ORAUT 2005]. The resultant values were input to the Integrated Modules for Bioassay Analysis (IMBA) computer program, and a fit to the data for each of the four radionuclides was performed to obtain intake rates for assigning dose distributions.

4.0 DATA

4.1 SELECTED BIOASSAY DATA

Data for each of the evaluated EDP codes were extracted from a series of database files that contain a version of the CER Dosimetry Database. These files were titled “tblORNL_Urinalysis_rawData,” for 1951–1978, 1979–1985, and 1986–1988.

4.2 ANALYSIS

A lognormal distribution for the annual data for each of the four radionuclides was assumed and the 50th and 84th percentiles were calculated using the method described in ORAUT-OTIB-0019 [ORAUT 2005]. The strontium data for 1951 through 1953 were combined due to the small amount of data available in those years. Tables A-1 through A-4 in Attachment A show the statistical analysis results for strontium, uranium, plutonium, and americium, respectively.

5.0 INTAKE MODELING

5.1 ASSUMPTIONS

All results were assumed to be representative of a full day (24 hours) of urinary excretion. Each result used in the intake calculation was assumed to be normally distributed, and a uniform absolute error of 1 was applied to all results to weight all results equally. A chronic exposure pattern was assumed; while this is unlikely for workers at ORNL, it approximates a series of acute intakes with unknown intake dates. Intakes were assumed to be via inhalation using a default breathing rate of 1.2 m^3/hr and a 5-µm activity median aerodynamic diameter particle size distribution.

5.2 BIOASSAY FITTING

IMBA and the Internal Dosimetry Tool (IDOT) software were used to fit the bioassay results to a series of inhalation intakes. Data for each radionuclide were fit as a series of chronic intakes.

Because type S strontium; type S uranium; types M, S, and SS plutonium isotopes; and type M americium isotopes at ORNL have very long half-lives and because the material is retained in the body for long periods, excretion results are not independent. For example, an intake in the early 1950s could contribute to urinary excretion in the 1980s and later. To avoid potential underestimation of intakes for people who worked at ORNL for relatively short periods, each intake was fit independently using only the bioassay results from the single intake period. This results in an

overestimate of intakes, particularly for assumed type SS or S exposures extending through multiple assumed intake periods.

5.3 RADIONUCLIDES AND MATERIAL TYPES

For each radionuclide, the bioassay results were entered into IMBA and/or IDOT with assumed material types as discussed in more detail in the following sections. The assumed 50th-percentile intakes that resulted are shown in the figures in Attachment A. In these figures, annual bioassay data used in the fits are shown as dark dots (●), and data that are not used in the fits are shown as lighter dots (●). For certain radionuclides and material types, it is necessary to show figures for both the composite intake over the entire data period and the individual plots of subsets of selected groups of years during the data period that were used to develop the composite figure. The composite plot shows the merged fit for all intake periods to the bioassay data. The IMBA output figures in Attachment A show the fit to the bioassay data for each annual intake period in terms of days after the date of initial data reporting. For example, for ^{90}Sr, day 1 equals June 1, 1951, and day 13,515 equals June 1, 1988.

5.3.1 Strontium-90

Strontium results were assumed to be ^{90}Sr. Because of the presence of ^{90}Sr both as an effluent from reactor operations and in a highly insoluble titanate form, bioassay results for ^{90}Sr were fit using type F and S material. Figure A-1 in Attachment A shows the fit to the 50th-percentile intake values for type F ^{90}Sr. Table A-5 summarizes the intake periods and rates for the 50th- and 84th-percentile values along with the geometric standard deviations (GSDs) for type F ^{90}Sr. The GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates.

Figures A-2 through A-6 show the fits corresponding to each of the subsets of years across the intake period used to develop the composite figure for type S ^{90}Sr. Figure A-7 shows the composite of the subsets of selected groups of years used to fit the 50th-percentile intake values for type S ^{90}Sr. Table A-6 summarizes the intake periods and rates for the 50th- and 84th-percentile values along with the calculated GSDs for type S ^{90}Sr. The same intake periods were applied to the 84th-percentile values for both ^{90}Sr type F and S material because the values followed a similar pattern; results of the individual fits are not shown here because they were largely in agreement. The urinalysis data for 1964 were insufficient to support a complete analysis and were therefore omitted from the sample set. The intake rate for 1964 was assumed to be the same as for 1963, the higher of the contiguous years.

5.3.2 Uranium

Because a variety of uranium enrichments and exposure conditions have been possible at the ORNL site, ^{234}U was assumed for the IMBA intake modeling even though the source data are for gross uranium in varying amounts, depending on the enrichment. This assumption does not affect the fitting of the data for intake determination (e.g., the same total intakes would be obtained for any enrichment that was assumed) because all uranium isotopes behave the same biokinetically and the isotopes considered in this analysis have long half-lives in relation to the assumed intake period. International Commission on Radiological Protection (ICRP) Publication 68 [ICRP 1995] dose coefficients (also referred to as dose conversion factors) for ^{234}U are 7% to 31% larger than those for ^{235}U, ^{236}U, and ^{238}U. Because of the varied isotopic compositions of the source terms, the ^{234}U dose conversion factor will overestimate doses for any combination of the uranium radioisotopes, but the assumption of intake of 100% ^{234}U is made to ensure the doses are favorable to the claimant.

Because uranium has been present in many chemical forms at ORNL, the bioassay data were fit using type F, M, and S material. Figures A-8 and A-9 in Attachment A show the fits for the 50th-percentile values for type F and M uranium, respectively. Table A-7 summarizes the intake periods for

the 50th- and 84th-percentile values along with the calculated GSDs for type F uranium, while Table A-8 lists similar information for type M uranium. Again, the GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates.

For type S uranium, Figures A-10 through A-16 show the fits corresponding to each of the subsets of years across the intake period used to develop the composite figure. Figure A-17 provides the composite of the subsets of selected groups of years used to fit the 50th-percentile intake values. Table A-9 summarizes the intake periods and rates for the 50th- and 84th-percentile values along with the calculated GSDs for type S uranium. Plots of the results of the fits to the 84th-percentile values for all three material types are not shown here because they were largely in agreement.

5.3.3 Plutonium

ICRP Publication 68 [ICRP 1995] assigns all forms of plutonium to types M and S. In addition, type SS is evaluated in accordance with ORAUT-OTIB-0049, *Estimating Doses for Plutonium Strongly Retained in the Lung* [ORAUT 2020]. Although the bioassay results are for all alpha-emitting isotopes of plutonium, the results were assumed to represent the concentration of ^{239}Pu alone. Figures A-18 through A-21 in Attachment A show the fits for type M material corresponding to each of the subsets of years across the intake period used to develop the composite figure. Figure A-22 shows the composite of the subsets of selected years used to fit the 50th-percentile intake values for type M plutonium. Table A-10 summarizes the intake periods and rates for the 50th- and 84th-percentile values along with the GSDs for type M plutonium. The GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates. Plots of the results of the individual fits to the 84th-percentile values for type M plutonium are not shown here because they were largely in agreement.

Figures A-23 through A-26 in Attachment A show the fits for type S material corresponding to each of the subsets of years across the intake period used to develop the composite figure. Figure A-27 shows the composite of the subsets of selected years used to fit the 50th-percentile intake values for type S plutonium. Table A-11 summarizes the intake period and rate for the 50th- and 84th-percentile values along with the GSDs for type S plutonium. Again, the GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates. Plots of the results of the individual fits to the 84th-percentile values for type S plutonium are not shown here because they were largely in agreement.

Figures A-28 through A-31 in Attachment A show the fits for type SS material corresponding to each of the subsets of years across the intake period used to develop the composite figure. Figure A-32 shows the composite of the subsets of selected years used to fit the 50th-percentile intake values for type SS plutonium. Table A-12 summarizes the intake period and rate for the 50th- and 84th-percentile values along with the GSDs for type SS plutonium. Again, the GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates. Plots of the results of the individual fits to the 84th-percentile values for type SS plutonium are not shown here because they were largely in agreement.

5.3.4 Americium-241

ICRP Publication 68 [ICRP 1995] assigns all forms of americium to type M. Figures A-33 and A-34 in Attachment A show the fits corresponding to each of the subsets of years across the intake period used to develop the composite figure. Figure A-35 shows the composite of the subsets of selected years used to fit the 50th-percentile intake values for type M ^{241}Am. Table A-13 summarizes the intake periods and rates for the 50th- and 84th-percentile values along with the GSDs for type M ^{241}Am. Again, the GSDs were determined by dividing the 84th-percentile intake rates by the 50th-percentile intake rates. The same intake periods were applied to the 84th-percentile values for type M ^{241}Am

because the values followed a similar pattern; results of the individual fits are not shown here because they were largely in agreement.

5.3.5 Additional Radionuclides

Hundreds of different radionuclides have been present at ORNL at some point during its operations. For fission and activation product mixtures, dose reconstructors should use the intake mixture ratios in the latest revision of ORAUT-OTIB-0054, *Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses* [ORAUT 2014]. ORAUT-OTIB-0054 is applicable for workers in the Reactor Division and the Tank Farms areas. It should not be used for workers from the Isotopes Separations Division or Isotope Development Center (Buildings 3030 to 3047).

6.0 ASSIGNMENT OF INTAKES AND DOSES

This section describes the derived intake rates and provides guidance for assigning doses. For each radionuclide, the 50th- and 95th-percentile intake rates along with the GSDs are provided in specific tables. In most cases, doses for individuals who were potentially exposed routinely should be calculated from the 50th-percentile intake rates by assuming the material type that results in the largest probability of causation. The GSD values have been adjusted from the values in the tables in Attachment A to allow for the addition of doses from different intake periods into a single input line for a given year in the Interactive RadioEpidemiological Program (IREP) input file and to ensure that none are less than 3, the value used when assigning intakes to individuals from person-specific bioassay results. For cases in which there is justification that the individual might have had intakes larger than the 50th-percentile intake rates, dose reconstructors should use the 95th-percentile intake rates input into IREP as a constant.

- Strontium-90. For ^{90}Sr, several intake periods were defined as listed in Table 6-1 for type F material and Table 6-2 for type S material. There were five intake periods defined for ^{90}Sr type F intakes and six for ^{90}Sr type S intakes.

Table 6-1. Combined ^{90}Sr type F intake periods and rates (dpm/d).

From	To	50th percentile	GSD	95th percentile
01/01/1951	12/31/1953	475.2	10.0	20,983
01/01/1954	12/31/1954	80.99	10.0	3,576
01/01/1955	12/31/1960	47.34	4.17	496
01/01/1961	12/31/1964	47.34	3.00	288
01/01/1965	12/31/1988	15.52	3.00	94.57

Table 6-2. Combined ^{90}Sr type S intake periods and rates (dpm/d).

From	To	50th percentile	GSD	95th percentile
01/01/1951	12/31/1953	24,646	9.53	1,005,436
01/01/1954	12/31/1954	7,232	9.53	295,030
01/01/1955	12/31/1960	2,379	5.73	42,030
01/01/1961	12/31/1964	2,379	3.00	14,496
01/01/1965	12/31/1983	795.0	3.00	4,844
01/01/1984	12/31/1988	425.5	4.51	5,070

- Uranium. Tables 6-3 through 6-5 list the calculated annual intake rates for uranium for 1951 through 1987 for types F, M, and S material, respectively. The intakes should be assumed to be 100% ^{234}U.

Table 6-3. Annual ^{234}U type F intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1955	11.19	3.08	71.20
01/01/1956	12/31/1956	4.213	6.71	96.51
01/01/1957	12/31/1958	1.942	9.25	75.43
01/01/1959	12/31/1961	5.171	3.48	40.22
01/01/1962	12/31/1963	1.881	6.71	43.09
01/01/1964	12/31/1984	0.413	3.08	2.63
01/01/1985	12/31/1987	0.0957	3.08	0.609

Table 6-4. Annual ^{234}U type M intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1955	47.03	3.33	340.2
01/01/1956	12/31/1956	11.45	9.70	480.9
01/01/1957	12/31/1958	7.49	9.70	314.6
01/01/1959	12/31/1961	21.81	3.33	157.8
01/01/1962	12/31/1963	6.56	7.24	170.3
01/01/1964	12/31/1984	1.641	3.33	11.87
01/01/1985	12/31/1987	0.294	3.33	2.127

Table 6-5. Annual ^{234}U type S intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1955	850.7	3.00	5,184
01/01/1956	12/31/1956	675.7	3.00	4,117
01/01/1957	12/31/1958	247.7	7.74	7,176
01/01/1959	12/31/1961	509	4.17	5,331
01/01/1962	12/31/1963	235.3	6.04	4,533
01/01/1964	12/31/1982	23.7	3.00	144.4
01/01/1983	12/31/1983	15.25	4.67	192.4
01/01/1984	12/31/1987	15.25	3.00	92.93

- Plutonium. Tables 6-6 through 6-8 list the calculated annual intake rates for plutonium for types M, S, and SS material, respectively, for 1951 through 1988. The intakes should be assumed to be 100% ^{239}Pu.

Table 6-6. Annual ^{239}Pu type M intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1952	40.75	3.0	248
01/01/1953	12/31/1959	10.98	7.9	329
01/01/1960	12/31/1968	10.98	3.0	66.9
01/01/1969	12/31/1984	7.35	3.0	44.8
01/01/1985	12/31/1988	1.614	4.2	17.1

Table 6-7. Annual ^{239}Pu type S intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1952	1,489	3.00	9,073
01/01/1953	12/31/1959	159.8	11.06	8,325
01/01/1960	12/31/1968	159.8	3.00	973
01/01/1969	12/31/1972	118.5	3.40	886
01/01/1973	12/31/1984	118.5	3.00	722
01/01/1985	12/31/1988	36.26	5.46	592

Table 6-8. Annual ^{239}Pu type SS intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1951	12/31/1952	5,730	3.00	34,916
01/01/1953	12/31/1959	1,440	8.26	46,466
01/01/1960	12/31/1968	1,440	3.00	8,775
01/01/1969	12/31/1972	1,060	3.31	7,598
01/01/1973	12/31/1984	1,060	3.00	6,459
01/01/1985	12/31/1988	229	5.20	3,445

- Americium-241. Table 6-9 lists the combined ^{241}Am type M material intake periods and rates for 1968 through 1988. There were two defined intake periods.

Table 6-9. Americium-241 type M intake periods and rates (dpm/d).

From	Years	50th percentile	GSD	95th percentile
01/01/1968	12/31/1984	6.673	3.00	40.66
01/01/1985	12/31/1988	2.207	3.00	13.45

6.1 CONTRIBUTION FROM ADDITIONAL RADIONUCLIDES

For ^{90}Sr, the calculated intake rates for type F material should be applied for all exposures unless claimant interview information or related bioassay results indicate there was a potential for exposure to strontium titanate ($SrTiO_3$) or unless the individual worked in a location where it was found (Building 3517), in which case type S intakes should be assigned. If an individual was exposed only to type S material (titanate), intakes of associated radionuclides as discussed in ORAUT-OTIB-0054 [ORAUT 2014] should not be included. ORAUT-OTIB-0054 is applicable for workers in the Reactor Division and the Tank Farms areas and in all other areas except for workers in Building 3517 or from the Isotopes Separations Division or Isotope Development Center (Buildings 3030 to 3047). When a type F ^{90}Sr intake is assigned, the worker should also be assigned intakes of associated radionuclides as discussed in the latest revision of ORAUT-OTIB-0054.

6.2 DOSE ASSIGNMENT

In most cases, doses to be assigned to individuals potentially exposed on a routine basis are calculated from the 50th-percentile intake rates; the material type resulting in the largest probability of causation is selected. The lognormal distribution should be selected in IREP with the calculated dose entered as Parameter 1 and the associated GSD as Parameter 2. The GSD is associated with the intake, so it is applied to all annual doses determined from the intake period, with the exception of ORAUT-OTIB-0054 [ORAUT 2014] intakes of associated radionuclides.

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ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM

LIST OF TABLES

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ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

Table A-1. Statistical summary of annual strontium 24-hour urinary excretion rates (dpm/d), 1951 to 1988.[a]

Effective bioassay date	GM (50th)	GM × GSD (84th)[b]	No. of samples	No. of employees
07/01/1952[c]	109.15	1,008.55	134	16
07/01/1954	24.68	241.98	246	162
07/01/1955	13.10	63.17	722	534
07/01/1956	13.54	82.88	705	538
07/01/1957	15.71	68.85	879	566
07/01/1958	17.01	75.45	1,394	620
07/01/1959	12.20	59.03	1,035	623
07/01/1960	15.67	65.07	624	364
07/01/1961	9.48	28.06	1,328	952
07/01/1962	12.04	29.49	2,440	1,579
07/01/1963	10.08	26.23	2,328	1,524
1964[d]	No data	No data	No data	No data
07/01/1965	4.86	15.75	2,203	1,649
07/01/1966	3.62	17.78	1,619	1,274
07/01/1967	3.35	12.86	1,609	1,332
07/01/1968	1.02	7.77	1,147	915
07/01/1969	3.89	8.96	1,295	1,028
07/01/1970	6.07	13.96	636	456
07/01/1971	6.91	15.08	607	437
07/01/1972	7.54	22.75	358	211
07/01/1973	5.18	13.45	397	316
07/01/1974	7.66	24.76	282	217
07/01/1975	5.27	10.68	290	239
07/01/1976	5.14	11.59	270	201
07/01/1977	5.19	11.58	168	120
07/01/1978	5.04	9.61	149	109
07/01/1979	2.44	6.68	215	169
07/01/1980	5.69	23.05	242	162
07/01/1981	3.04	7.22	159	127
07/01/1982	5.23	12.06	146	98
07/01/1983	5.71	14.48	145	96
07/01/1984	4.38	14.14	136	88
07/01/1985	2.11	5.93	161	134
07/01/1986	0.67	2.88	221	168
07/01/1987	3.37	15.98	228	151
07/01/1988	0.56	1.96	275	225

a. GM = geometric mean; No data = insufficient data for analysis.
b. The actual GSDs from the statistical analyses are used as input into the intake modeling. The GSDs of the results of the intake modeling are adjusted to a minimum of 3.00 for assignment of intakes.
c. This period includes data for 01/01/1951 through 12/31/1953.
d. See Section 5.3.1 for discussion of evaluation of 1964.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

Table A-2. Statistical summary of annual uranium 24-hour urinary excretion rates (dpm/d), 1951 to 1987.

Effective bioassay date	GM (50th)	GM × GSD (84th)[a]	No. of samples	No. of employees
07/01/1951	3.41	7.81	351	262
07/01/1952	2.88	8.01	722	419
07/01/1953	3.64	7.54	615	494
07/01/1954	2.27	5.46	851	665
07/01/1955	3.07	9.34	823	591
07/01/1956	1.20	8.16	783	531
07/01/1957	0.50	3.65	942	664
07/01/1958	0.64	4.74	992	553
07/01/1959	1.43	6.93	745	461
07/01/1960	1.36	3.97	506	324
07/01/1961	1.52	5.73	686	456
07/01/1962	0.52	3.57	439	290
07/01/1963	0.58	3.24	698	389
07/01/1964	0.25	1.29	875	541
07/01/1965	0.17	0.62	1,462	1,178
07/01/1966	0.18	0.52	782	597
07/01/1967	0.09	0.21	687	530
07/01/1968	0.13	0.34	512	324
07/01/1969	0.10	0.33	457	268
07/01/1970	0.16	0.65	281	176
07/01/1971	0.09	0.26	288	201
07/01/1972	0.13	0.39	256	145
07/01/1973	0.07	0.30	278	206
07/01/1974	0.06	0.22	188	138
07/01/1975	0.08	0.32	219	149
07/01/1976	0.10	0.46	229	135
07/01/1977	0.20	0.48	191	131
07/01/1978	0.14	0.31	240	165
07/01/1979	0.14	0.52	318	213
07/01/1980	0.11	0.39	261	189
07/01/1981	0.13	0.22	179	145
07/01/1982	0.17	0.31	141	99
07/01/1983	0.12	0.28	167	106
07/01/1984	0.10	0.19	203	141
07/01/1985	0.07	0.17	217	158
07/01/1986	0.04	0.08	163	128
07/01/1987	0.00	0.03	212	164

a. The actual GSDs from the statistical analyses are used as input into the intake modeling. The GSDs of the results of the intake modeling are adjusted to a minimum of 3.00 for assignment of intakes.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

Table A-3. Statistical summary of annual plutonium 24-hour urinary excretion rates (dpm/d), 1951 to 1988.

Effective bioassay date	GM (50th)	GM × GSD (84th)[a]	No. of samples	No. of employees
07/01/1951	0.13	0.30	507	260
07/01/1952	0.11	0.31	668	394
07/01/1953	0.04	0.14	446	394
07/01/1954	0.07	0.36	972	583
07/01/1955	0.07	0.26	740	525
07/01/1956	0.04	0.36	627	473
07/01/1957	0.14	0.73	674	423
07/01/1958	0.15	0.52	785	400
07/01/1959	0.12	0.62	889	460
07/01/1960	0.13	0.28	1,927	595
07/01/1961	0.07	0.21	1,758	983
07/01/1962	0.01	0.08	2,680	1,658
07/01/1963	0.01	0.09	2,825	1,624
07/01/1964	0.08	0.23	2,147	1,446
07/01/1965	0.13	0.26	1,237	746
07/01/1966	0.12	0.21	1,179	803
07/01/1967	0.10	0.19	1,247	927
07/01/1968	0.12	0.24	1,262	775
07/01/1969	0.04	0.17	1,356	927
07/01/1970	0.08	0.19	828	481
07/01/1971	0.06	0.23	792	484
07/01/1972	0.06	0.18	686	350
07/01/1973	0.03	0.11	675	420
07/01/1974	0.06	0.12	529	350
07/01/1975	0.04	0.12	487	335
07/01/1976	0.05	0.13	532	341
07/01/1977	0.07	0.15	418	272
07/01/1978	0.06	0.15	431	262
07/01/1979	0.08	0.14	380	219
07/01/1980	0.05	0.11	320	215
07/01/1981	0.09	0.16	323	224
07/01/1982	0.10	0.17	345	226
07/01/1983	0.07	0.13	329	211
07/01/1984	0.07	0.11	370	237
07/01/1985	0.01	0.05	368	253
07/01/1986	0.01	0.04	297	212
07/01/1987	0.01	0.04	234	185
07/01/1988	0.00	0.03	169	128

a. The actual GSDs from the statistical analyses are used as input into the intake modeling. The GSDs of the results of the intake modeling are adjusted to a minimum of 3.00 for assignment of intakes.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

Table A-4. Statistical summary of annual americium 24-hour urinary excretion rates (dpm/d), 1968 to 1987.

Effective bioassay date	GM (50th)	GM × GSD (84th)[a]	No. of samples	No. of employees
07/01/1968	0.12	0.31	405	216
07/01/1969	0.10	0.42	455	253
07/01/1970	0.10	0.33	514	267
07/01/1971	0.09	0.24	444	262
07/01/1972	0.12	0.27	503	271
07/01/1973	0.09	0.16	547	336
07/01/1974	0.08	0.15	351	206
07/01/1975	0.12	0.30	367	246
07/01/1976	0.15	0.52	475	274
07/01/1977	0.11	0.18	358	223
07/01/1978	0.10	0.18	403	241
07/01/1979	0.10	0.17	279	196
07/01/1980	0.10	0.14	267	189
07/01/1981	0.07	0.17	289	213
01/01/1983	0.10	0.17	561	272
07/01/1984	0.10	0.15	345	225
07/01/1985	0.05	0.09	342	258
07/01/1986	0.01	0.05	280	217
07/01/1987	0.01	0.04	199	181

a. The actual GSDs from the statistical analyses are used as input into the intake modeling. The GSDs of the results of the intake modeling are adjusted to a minimum of 3.00 for assignment of intakes.

Table A-5. Type F ^{90}Sr intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1953	475.2	4,389	9.24
01/01/1954	12/31/1954	80.99	810.4	10.04
01/01/1955	12/31/1960	47.34	197.3	4.17
01/01/1961	12/31/1964	47.34	62.43	1.32
01/01/1965	12/31/1988	15.52	36.88	2.38

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

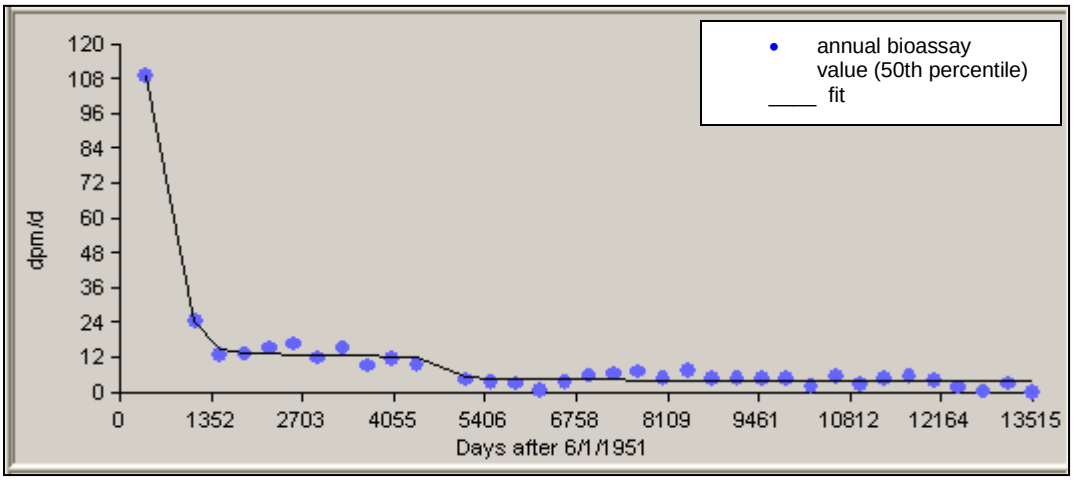

Figure A-1. Assumed ^{90}Sr intake, 1951 to 1988, 50th-percentile results, type F. The first bioassay datum with an effective bioassay date of 07/01/1952 is based on data for 01/01/1951 through 12/31/1953.

Table A-6. Type S ^{90}Sr intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1953	24,646	227,730	9.24
01/01/1954	12/31/1954	7,232	68,924	9.53
01/01/1955	12/31/1960	2,379	13,628	5.73
01/01/1961	12/31/1964	2,389	6,431	2.69
01/01/1965	12/31/1983	795.0	1,917	2.41
01/01/1984	12/31/1988	425.5	1,917	4.51

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.0.

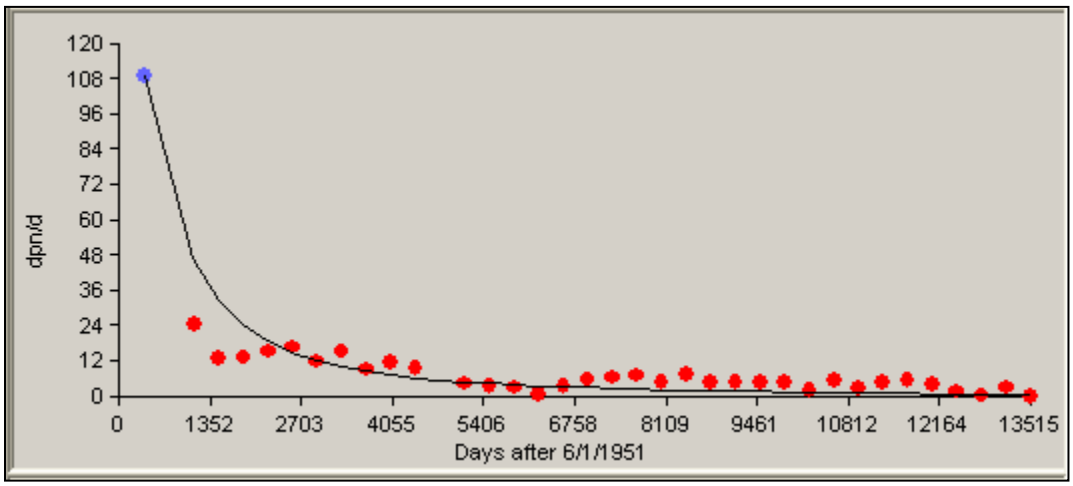

Figure A-2. Assumed ^{90}Sr intake, 1951 to 1953, 50th-percentile results, type S. The first bioassay datum with an effective bioassay date of 07/01/1952 is based on data for 01/01/1951 through 12/31/1953.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

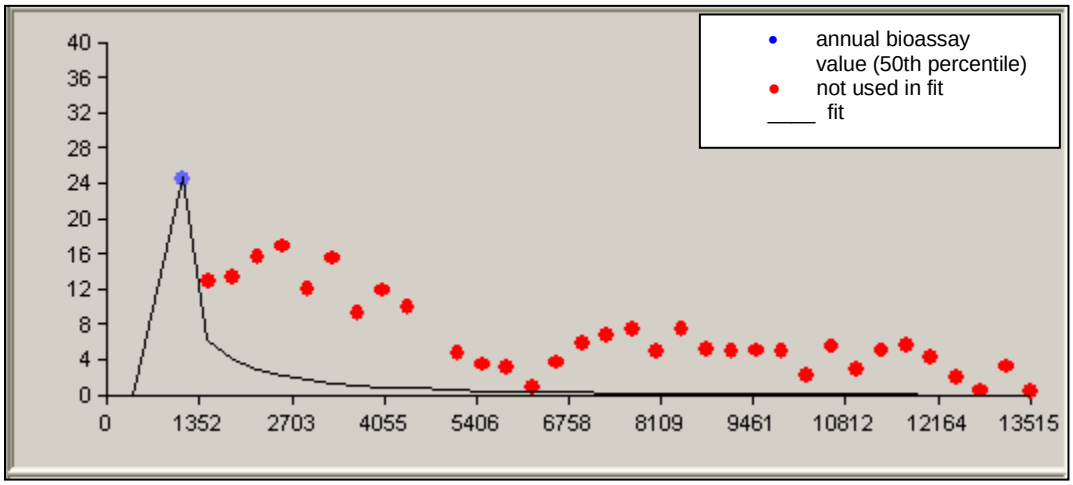

Figure A-3. Assumed ^{90}Sr intake, 1954, 50th-percentile results, type S.

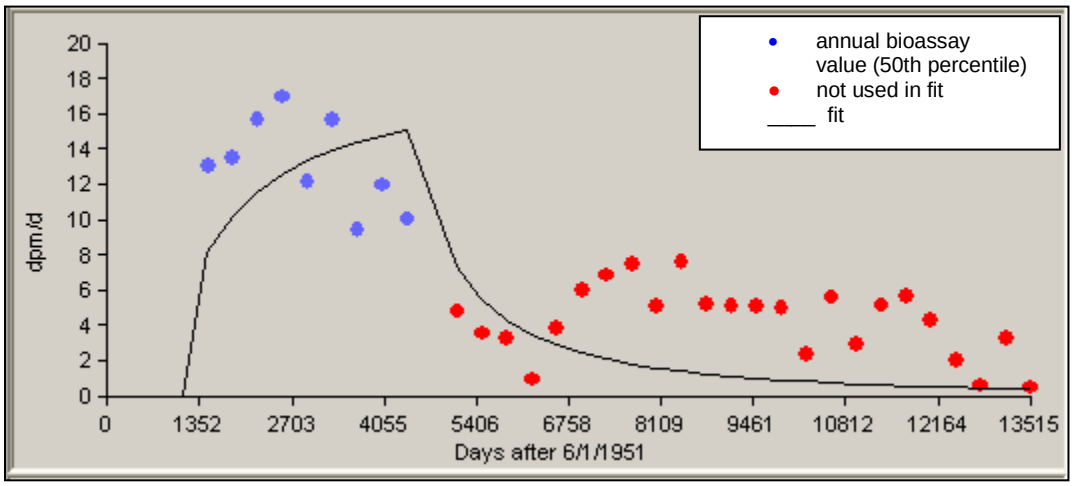

Figure A-4. Assumed ^{90}Sr intake, 1955 to 1964, 50th-percentile results, type S.

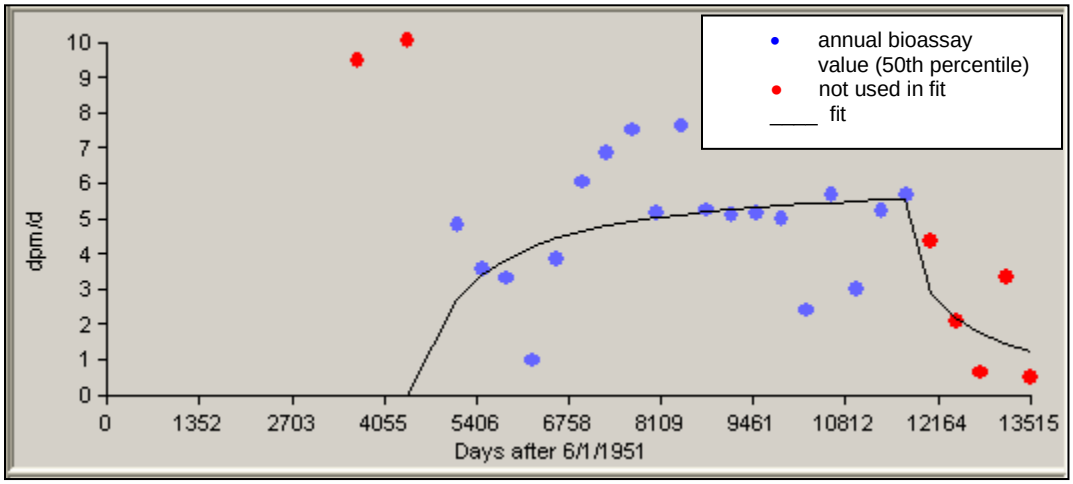

Figure A-5. Assumed ^{90}Sr intake, 1965 to 1983, 50th-percentile results, type S.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

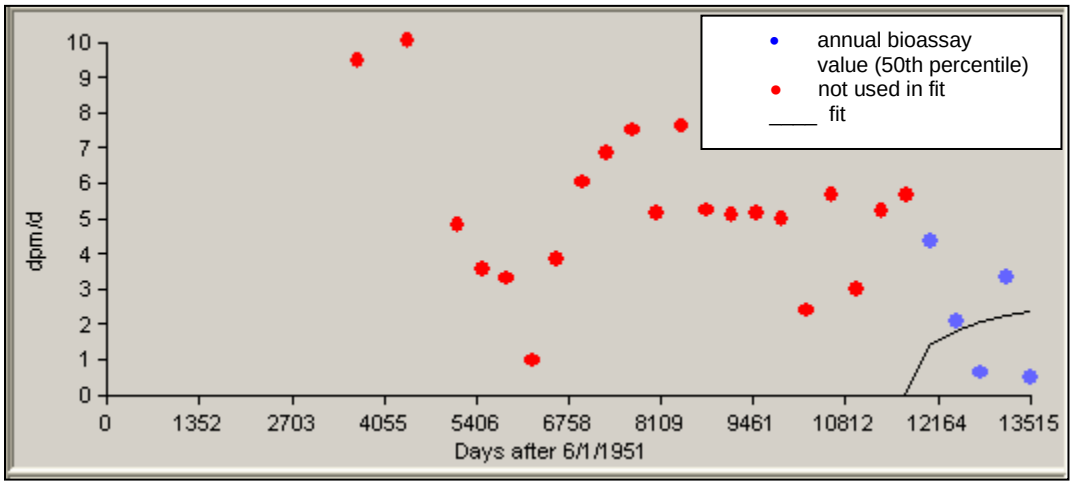

Figure A-6. Assumed ^{90}Sr intake, 1983 to 1988, 50th-percentile results, type S.

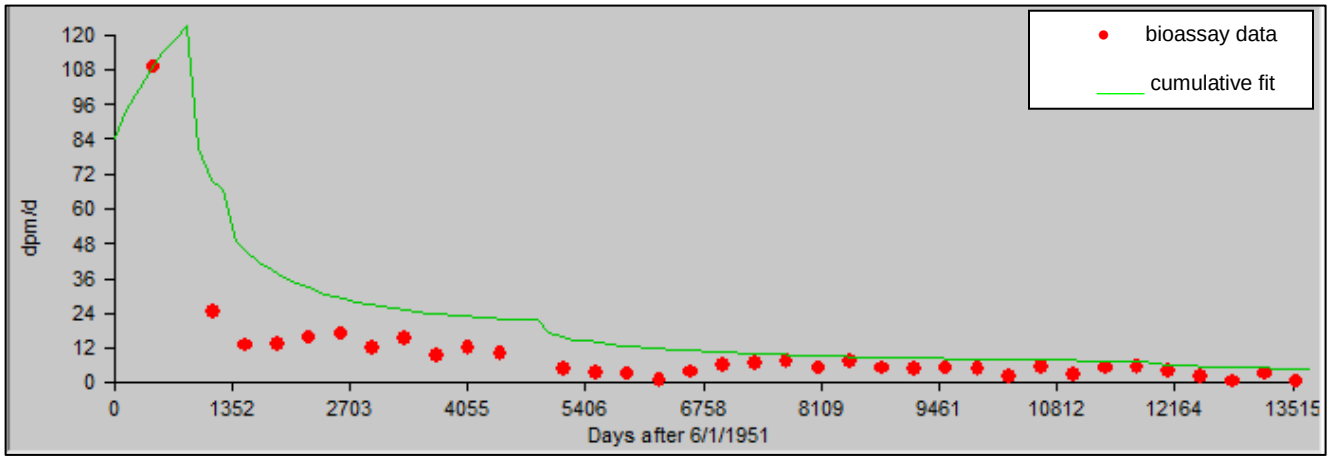

Figure A-7. Predicted cumulative ^{90}Sr excretion rate from independently fit intakes, 1951 to 1988, 50th-percentile results, type S.

Table A-7. Type F uranium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1955	11.19	28.28	2.53
01/01/1956	12/31/1956	4.213	28.28	6.71
01/01/1957	12/31/1958	1.942	17.97	9.25
01/01/1959	12/31/1961	5.171	17.97	3.48
01/01/1962	12/31/1963	1.881	12.05	6.41
01/01/1964	12/31/1984	0.413	1.272	3.08
01/01/1985	12/31/1987	0.0957	0.227	2.37

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

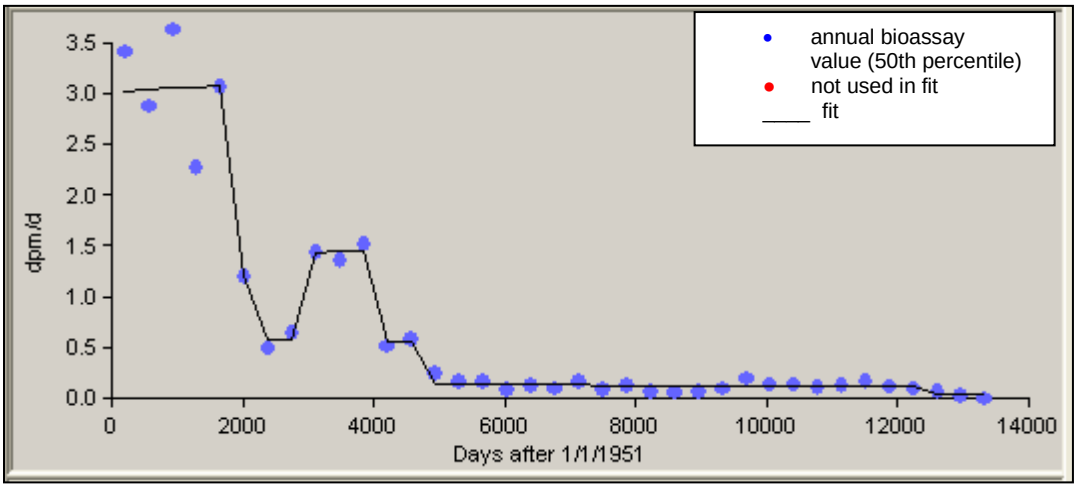

Figure A-8. Assumed uranium intake, 1951 to 1987, 50th-percentile results, type F.

Table A-8. Type M uranium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1955	47.03	117.8	2.50
01/01/1956	12/31/1956	11.45	117.8	10.29
01/01/1957	12/31/1958	7.49	72.66	9.70
01/01/1959	12/31/1961	21.81	72.66	3.33
01/01/1962	12/31/1963	6.56	47.49	7.24
01/01/1964	12/31/1984	1.641	4.809	2.93
01/01/1985	12/31/1987	0.294	0.659	2.24

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

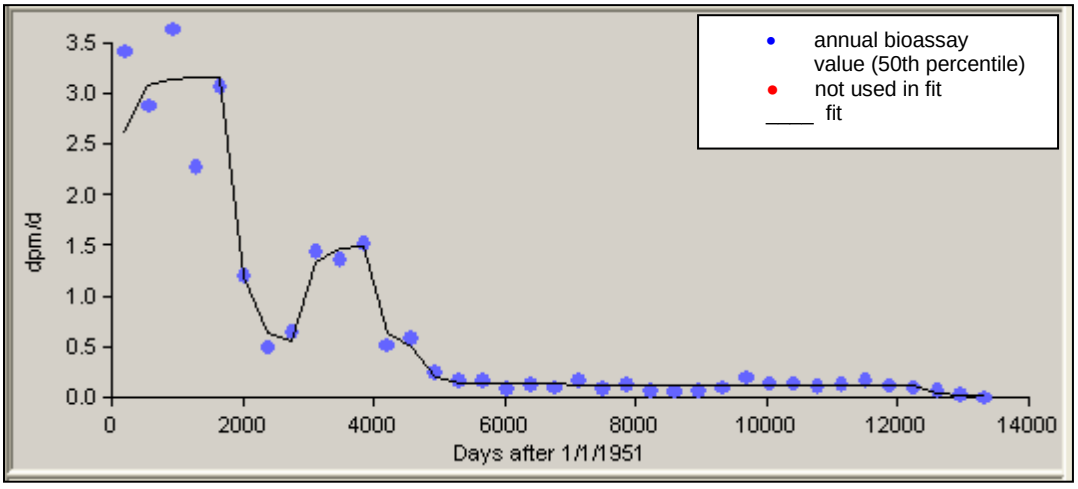

Figure A-9. Assumed uranium intake, 1951 to 1987, 50th-percentile results, type M.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

Table A-9. Type S uranium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1955	850.7	2,048	2.41
01/01/1956	12/31/1956	675.7	2,048	3.03
01/01/1957	12/31/1958	247.7	1,917	7.74
01/01/1959	12/31/1961	509	1,917	3.77
01/01/1962	12/31/1963	235.3	1,422	6.04
01/01/1964	12/31/1982	23.7	71.203	3.00
01/01/1983	12/31/1983	15.25	71.203	4.67
01/01/1984	12/31/1987	15.25	31.58	2.07

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

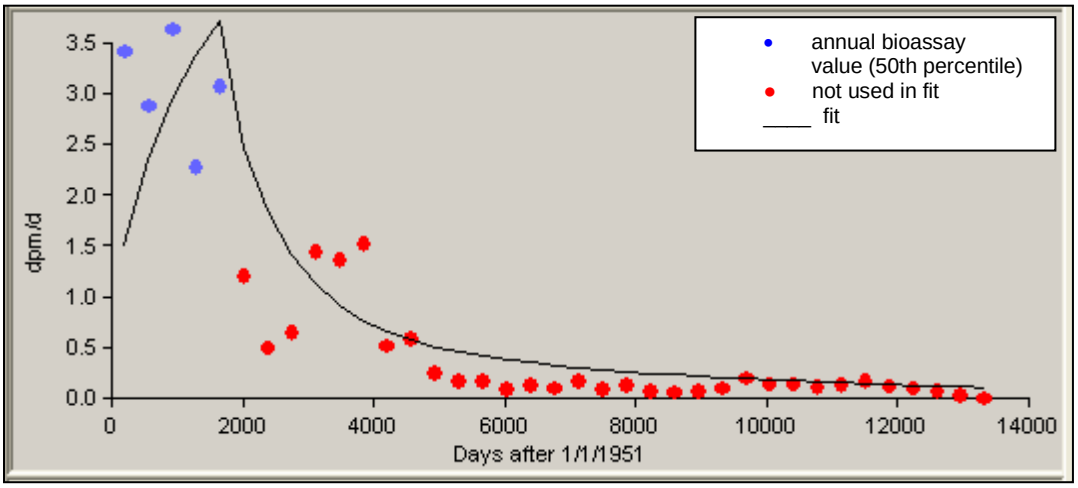

Figure A-10. Assumed uranium intake, 1951 to 1955, 50th-percentile results, type S.

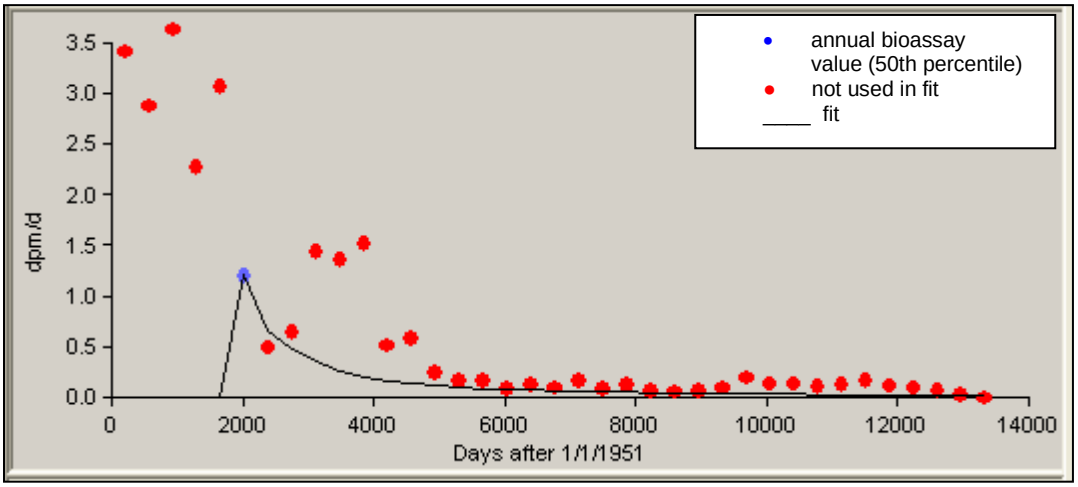

Figure A-11. Assumed uranium intake, 1956, 50th-percentile results, type S.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

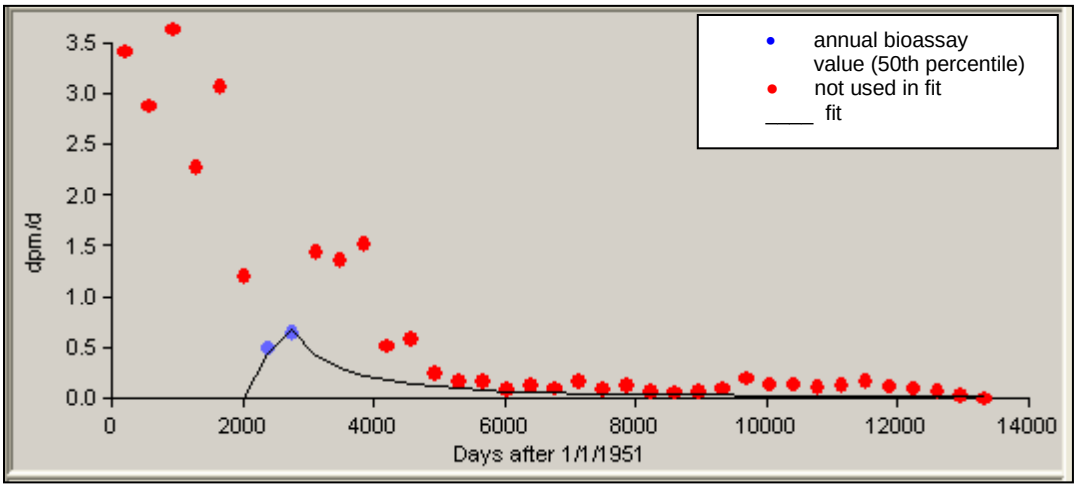

Figure A-12. Assumed uranium intake, 1957 to 1958, 50th-percentile results, type S.

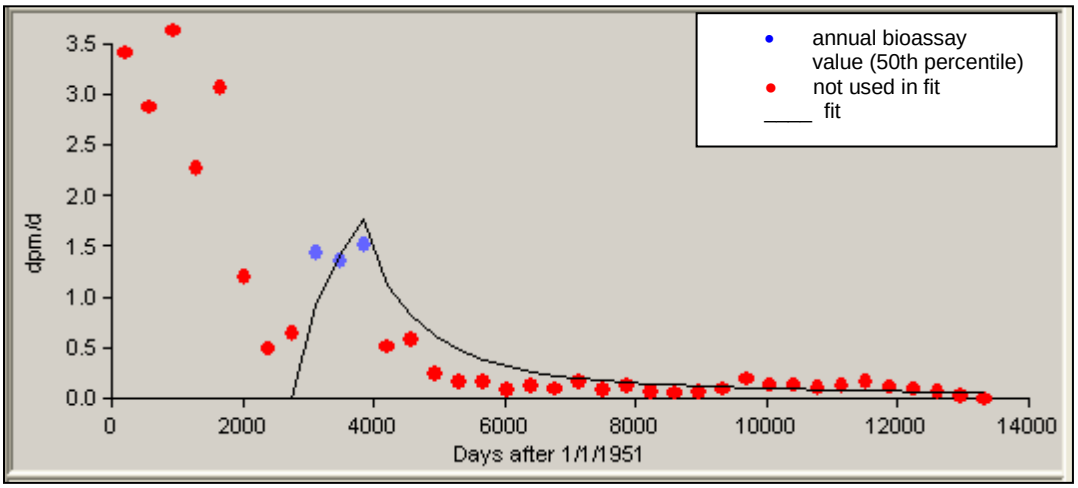

Figure A-13. Assumed uranium intake, 1959 to 1961, 50th-percentile results, type S.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

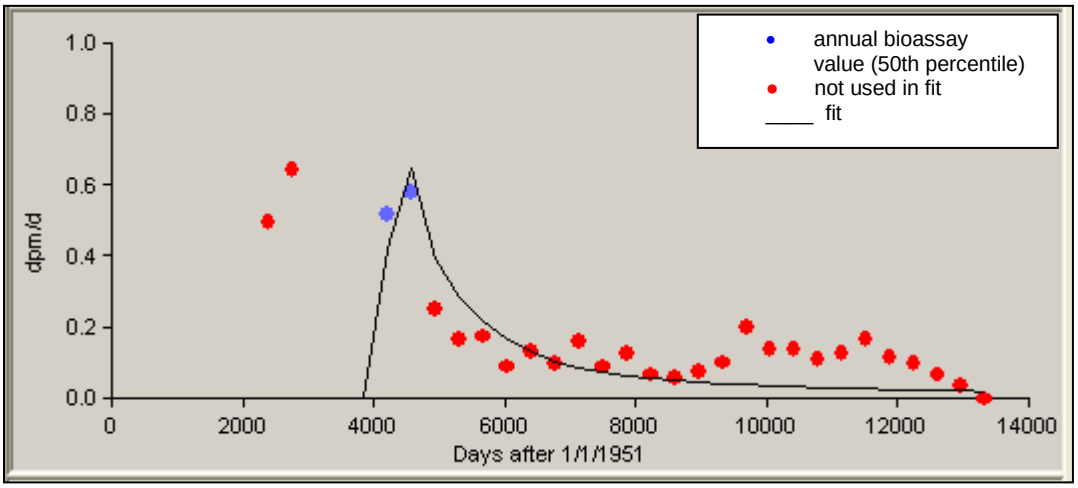

Figure A-14. Assumed uranium intake, 1962 to 1963, 50th-percentile results, type S.

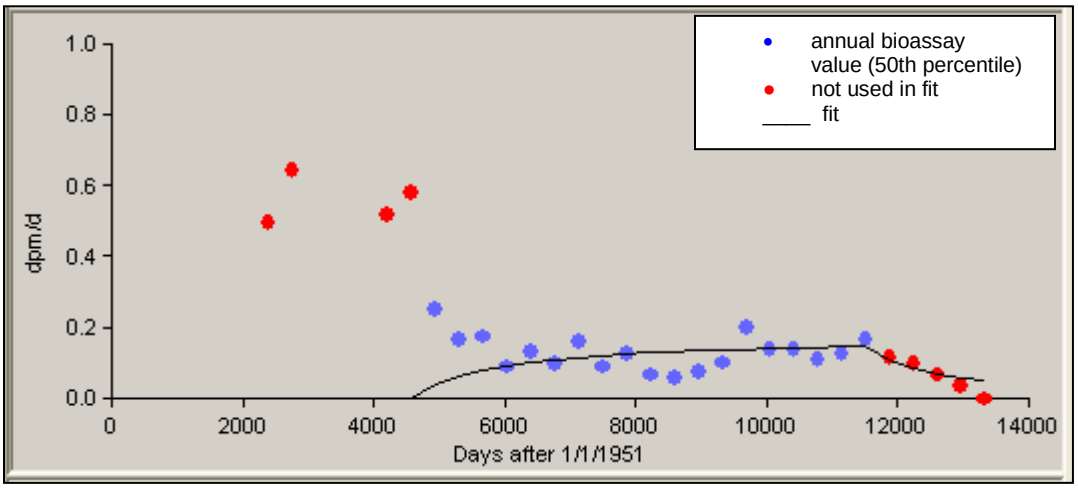

Figure A-15. Assumed uranium intake, 1964 to 1982, 50th-percentile results, type S.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

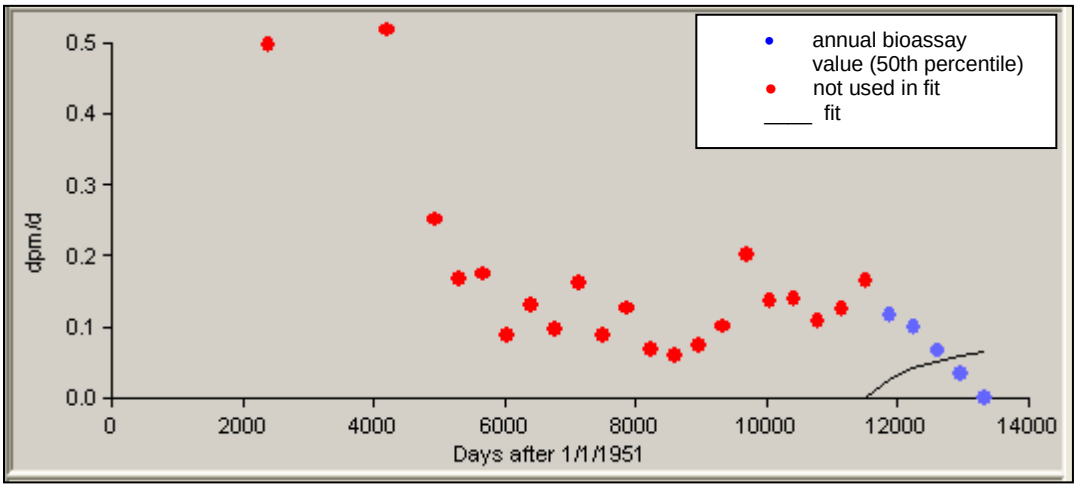

Figure A-16. Assumed uranium intake, 1983 to 1987, 50th-percentile results, type S.

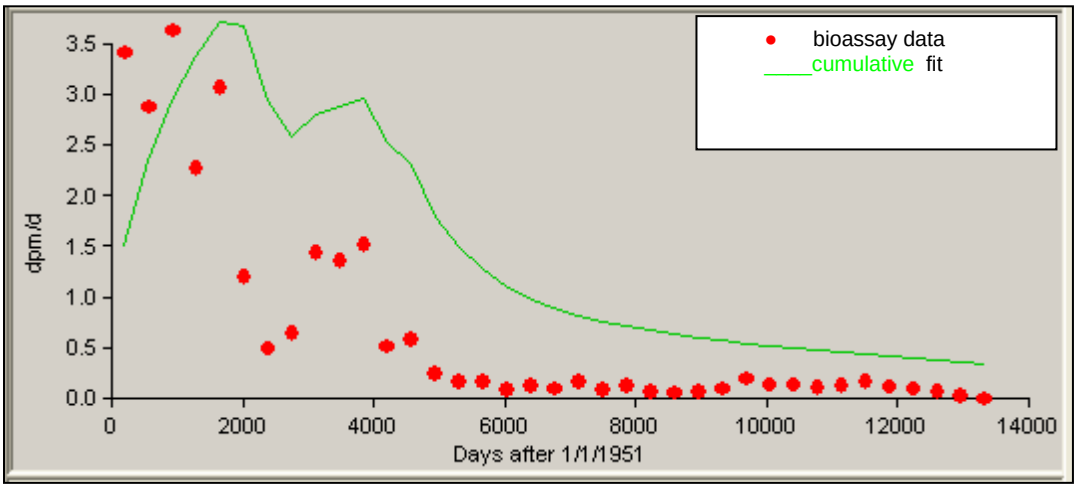

Figure A-17. Predicted cumulative uranium excretion rate from independently fit intakes, 1951 to 1987, 50th-percentile, type S.

Table A-10. Type M plutonium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1952	40.75	109.8	2.69
01/01/1953	12/31/1959	10.98	86.42	7.87
01/01/1960	12/31/1968	10.98	22.45	2.04
01/01/1969	12/31/1984	7.35	22.45	3.05
01/01/1985	12/31/1988	1.614	6.811	4.22

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

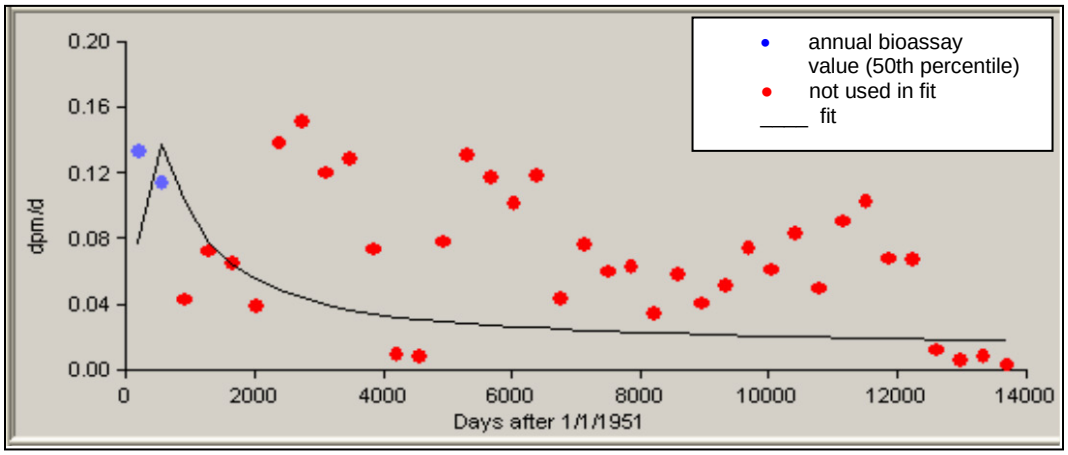

Figure A-18. Assumed plutonium intake, 1951 to 1952, 50th-percentile results, type M.

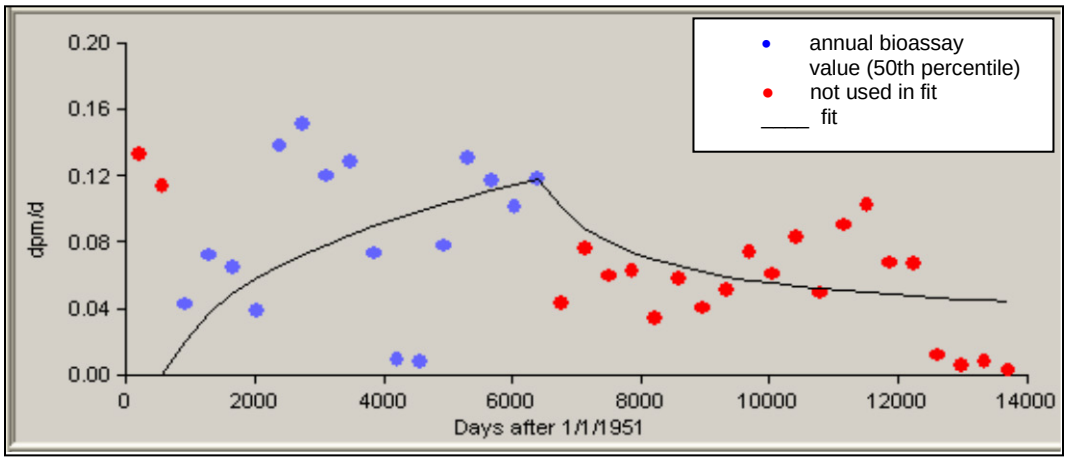

Figure A-19. Assumed plutonium intake, 1953 to 1968, 50th-percentile results, type M.

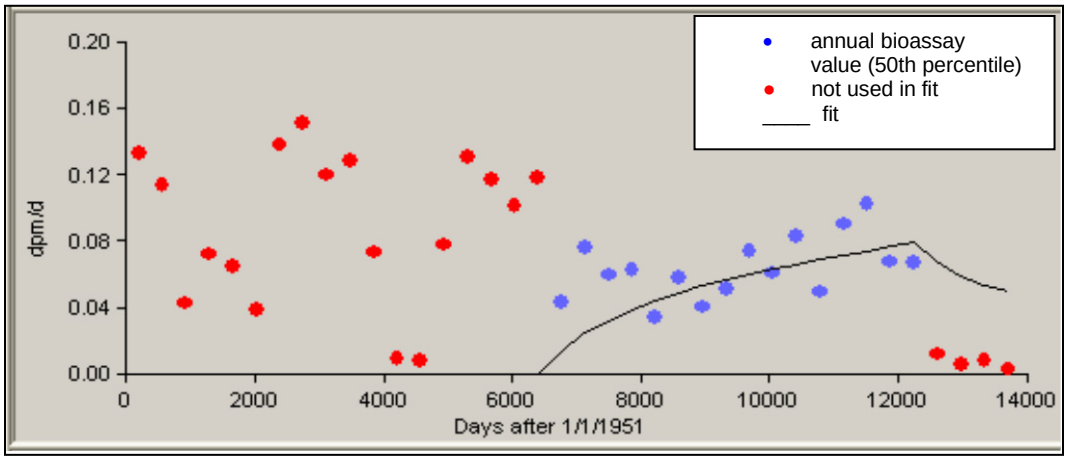

Figure A-20. Assumed plutonium intake, 1969 to 1984, 50th-percentile results, type M.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

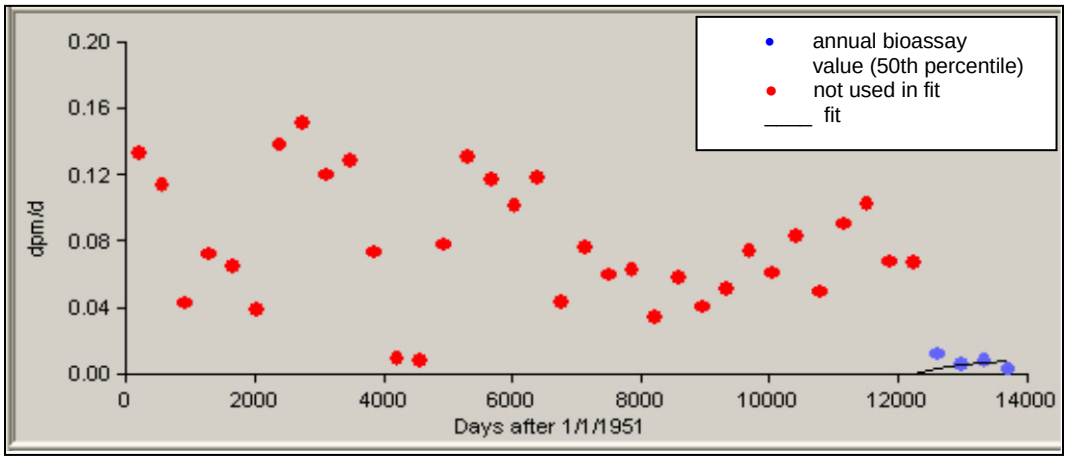

Figure A-21. Assumed plutonium intake, 1985 to 1988, 50th-percentile results, type M.

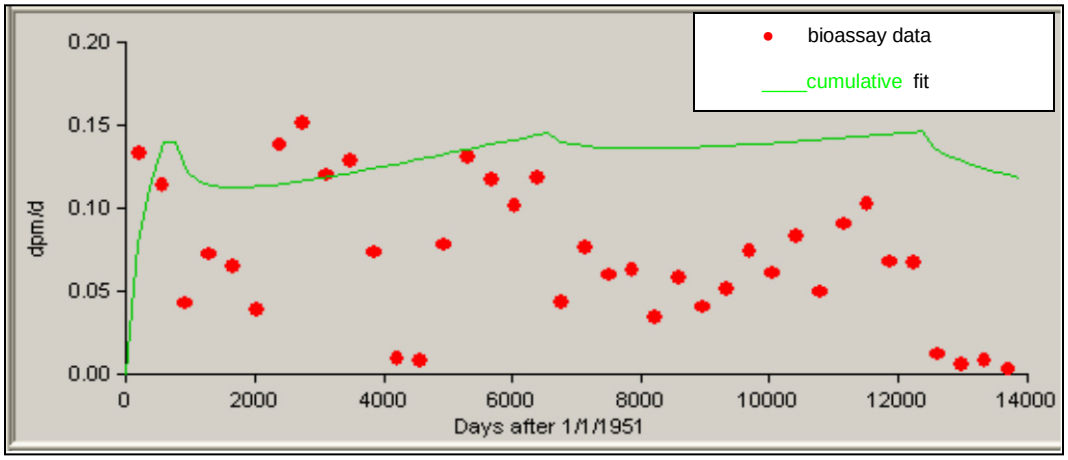

Figure A-22. Predicted cumulative plutonium intake, 1951 to 1988, 50th-percentile composite results, type M.

Table A-11. Type S plutonium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1952	1,489	3,874	2.60
01/01/1953	12/31/1959	159.8	1,767	11.06
01/01/1960	12/31/1968	159.8	402.5	2.52
01/01/1969	12/31/1984	118.5	402.5	3.40
01/01/1985	12/31/1988	36.26	198	5.46

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

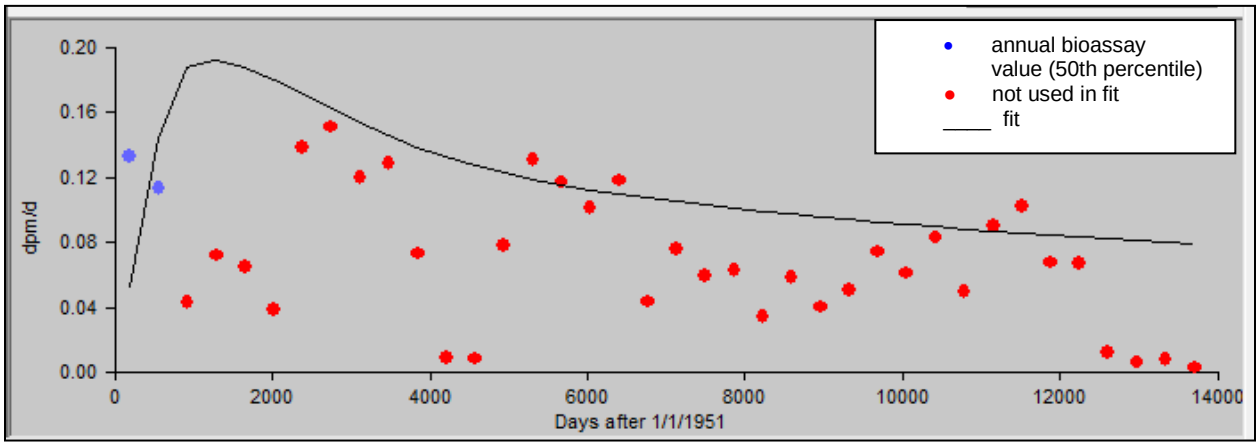

Figure A-23. Assumed plutonium intake, 1951 to 1952, 50th-percentile results, type S.

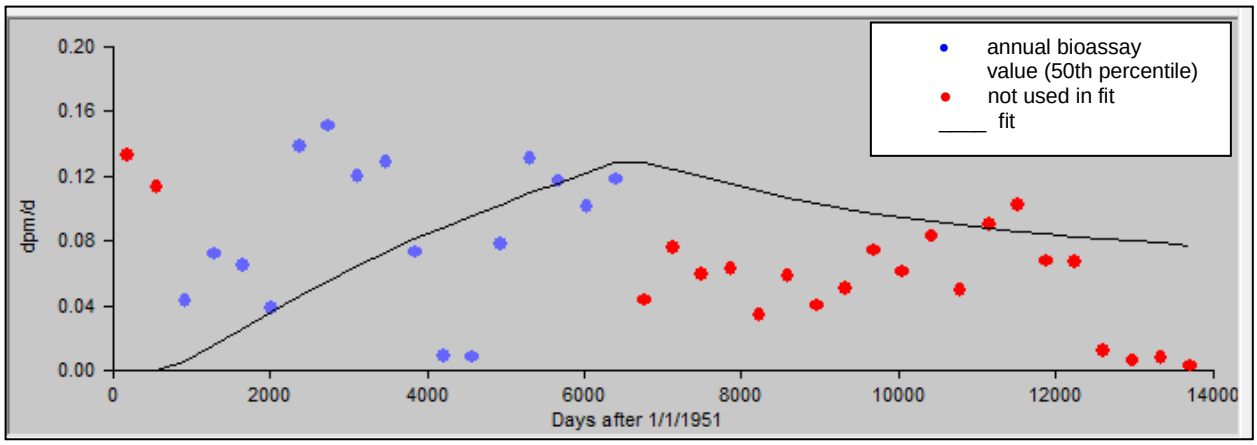

Figure A-24. Assumed plutonium intake, 1953 to 1968, 50th-percentile results, type S.

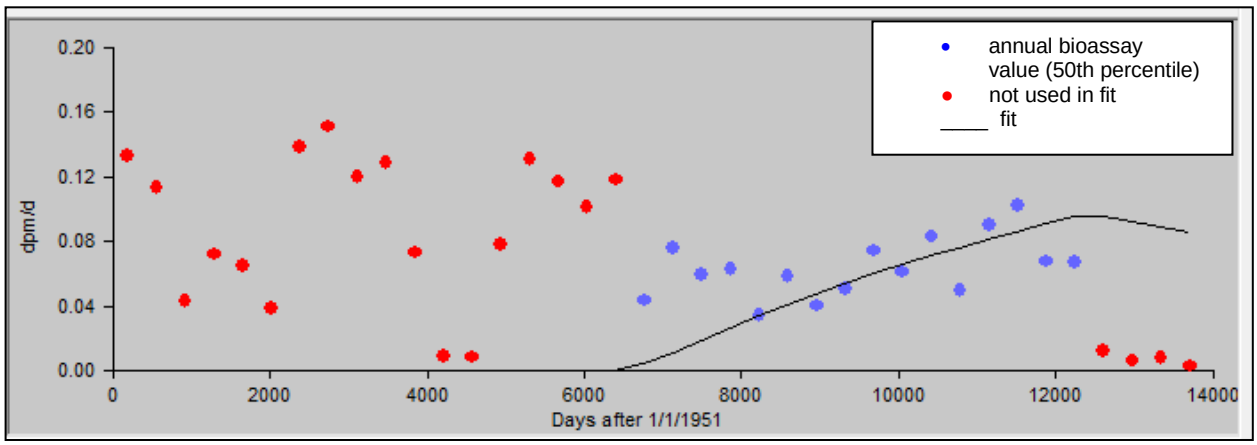

Figure A-25. Assumed plutonium intake, 1969 to 1984, 50th-percentile results, type S.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

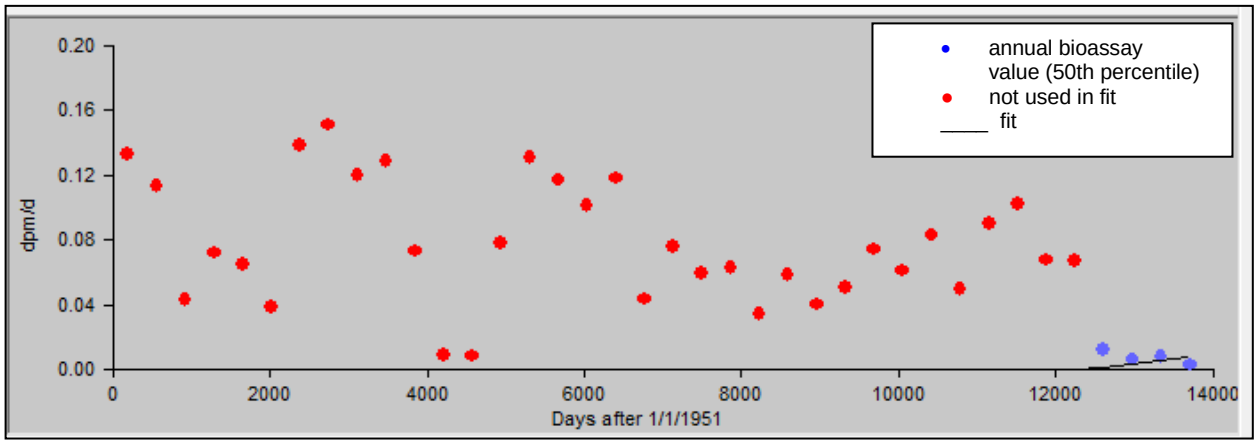

Figure A-26. Assumed plutonium intake, 1985 to 1988, 50th-percentile results, type S.

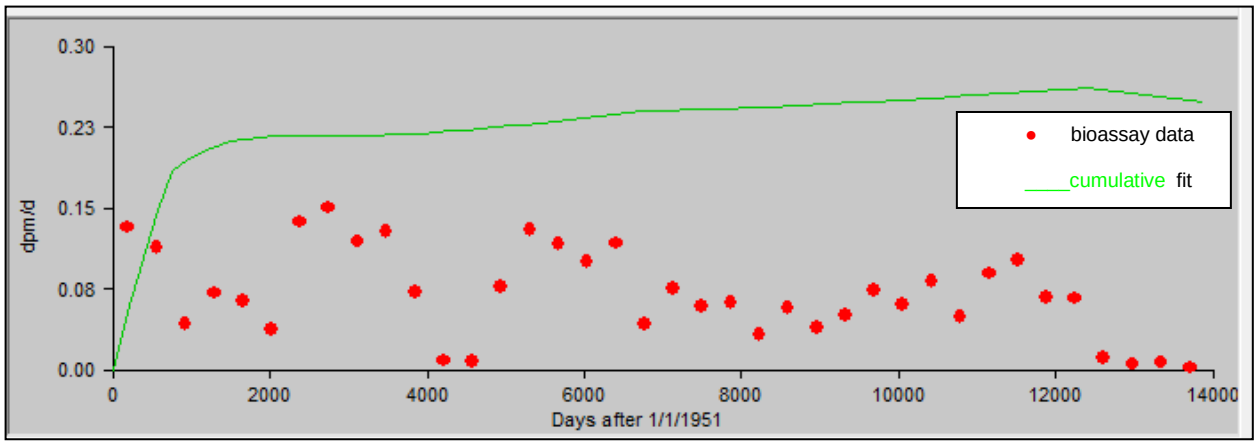

Figure A-27. Predicted cumulative plutonium intake, 1951 to 1988, 50th-percentile composite results, type S.

Table A-12. Type SS plutonium intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1951	12/31/1952	5,730	14,500	2.53
01/01/1953	12/31/1959	1,440	11,900	8.26
01/01/1960	12/31/1968	1,440	3,510	2.44
01/01/1969	12/31/1984	1,060	3,510	3.31
01/01/1985	12/31/1988	229	1,190	5.20

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

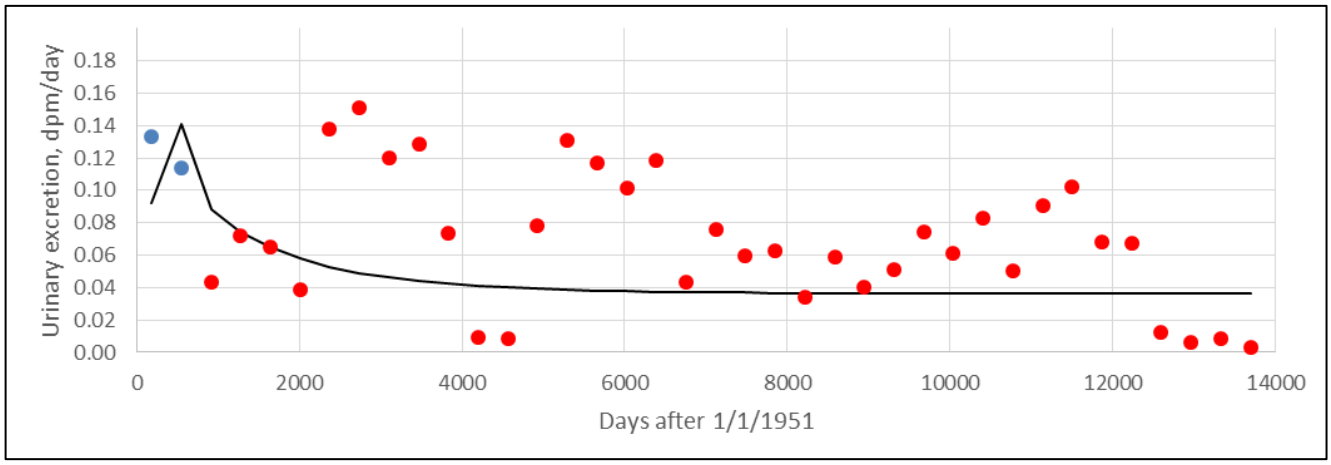

Figure A-28. Assumed plutonium intake, 1951 to 1952, 50th-percentile results, type SS.

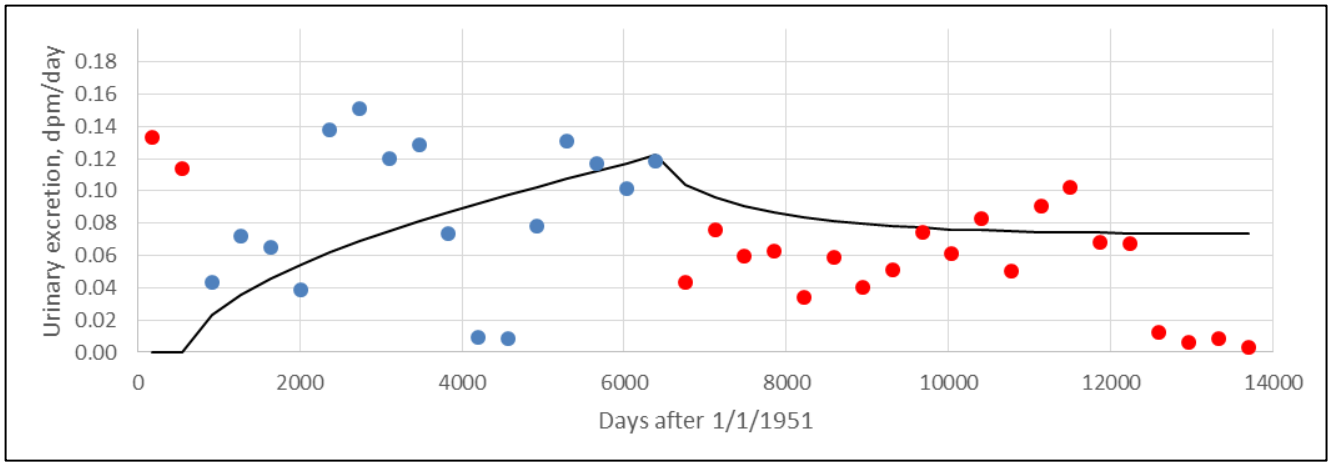

Figure A-29. Assumed plutonium intake, 1953 to 1968, 50th-percentile results, type SS.

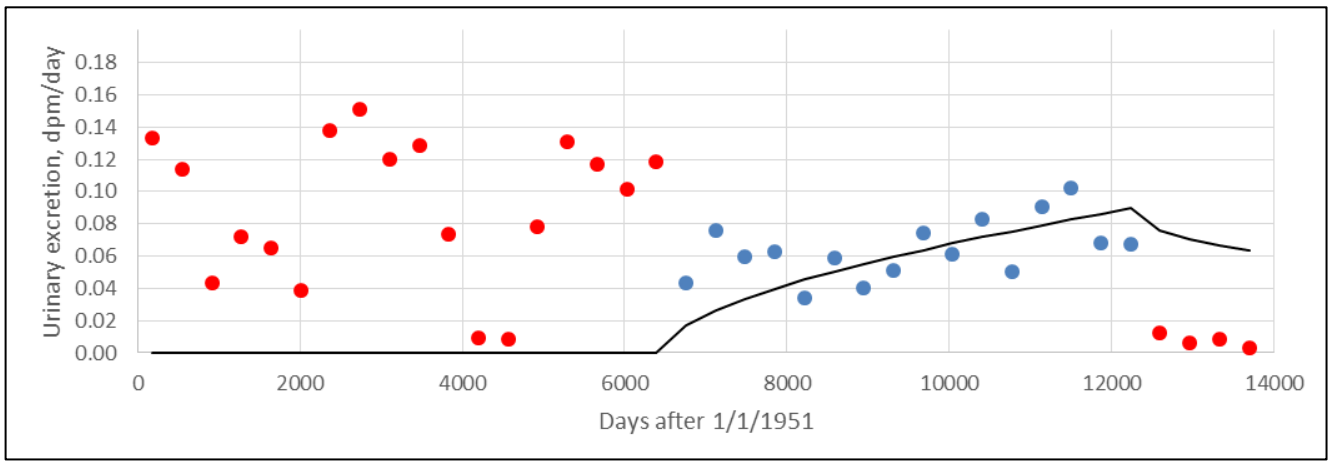

Figure A-30. Assumed plutonium intake, 1969 to 1984, 50th-percentile results, type SS.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

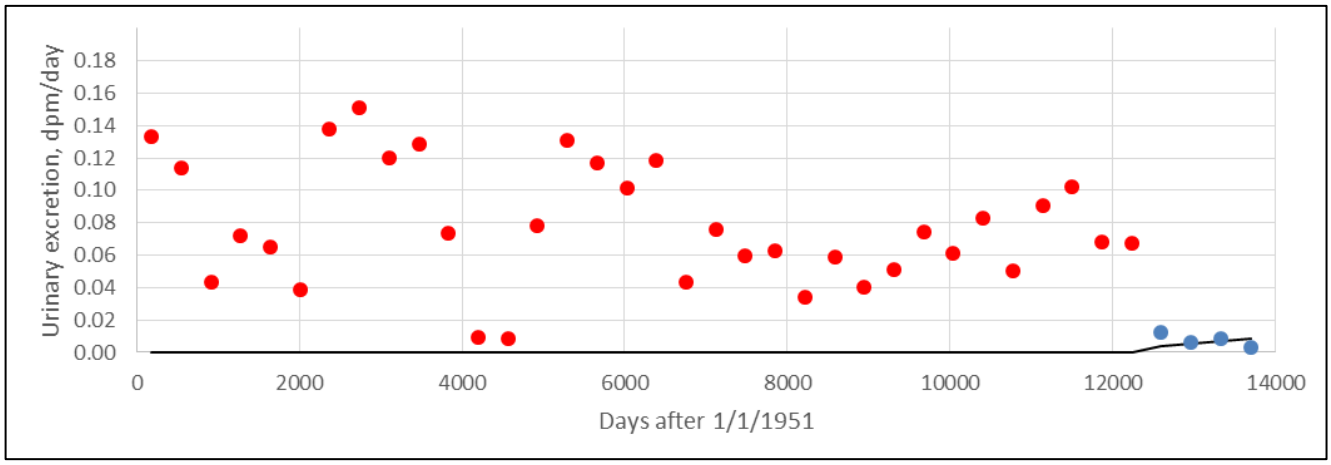

Figure A-31. Assumed plutonium intake, 1985 to 1988, 50th-percentile results, type SS.

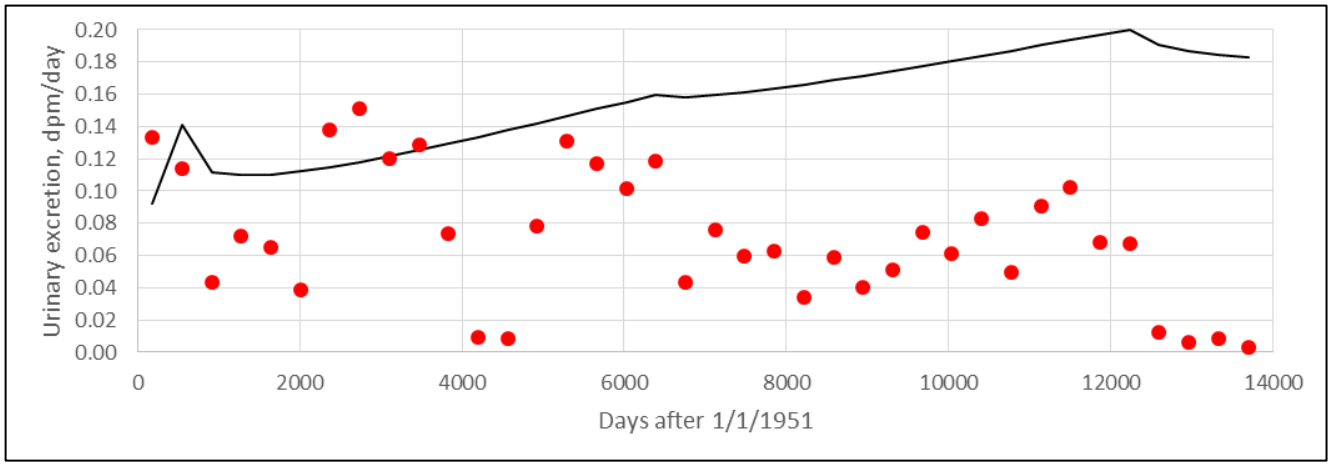

Figure A-32. Predicted cumulative plutonium intake, 1951 to 1988, 50th-percentile composite results, type SS.

Table A-13. Type M ^{241}Am intake periods and rates (dpm/d).

Start	End	50th percentile	84th percentile	GSD[a]
01/01/1968	12/31/1984	6.673	14.61	2.19
01/01/1985	12/31/1988	2.207	6.659	2.99

a. The actual GSDs from the results of the intake modeling are presented here. These GSDs are adjusted to a minimum of 3.00 for assignment of intakes as discussed in Section 6.

ATTACHMENT A
STATISTICAL ANALYSIS RESULTS FOR
STRONTIUM, URANIUM, PLUTONIUM, AND AMERICIUM (continued)

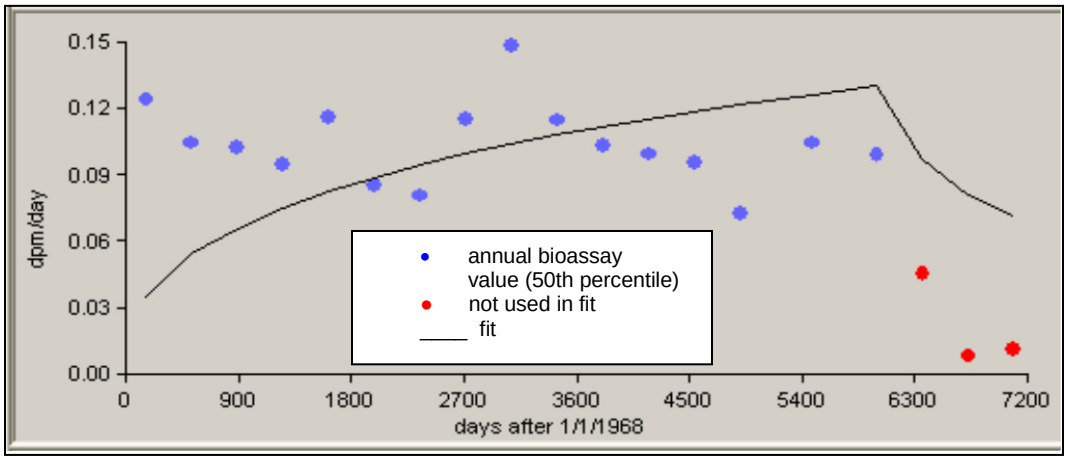

Figure A-33. Assumed ^{241}Am intake, 1968 to 1984, 50th-percentile results, type M.

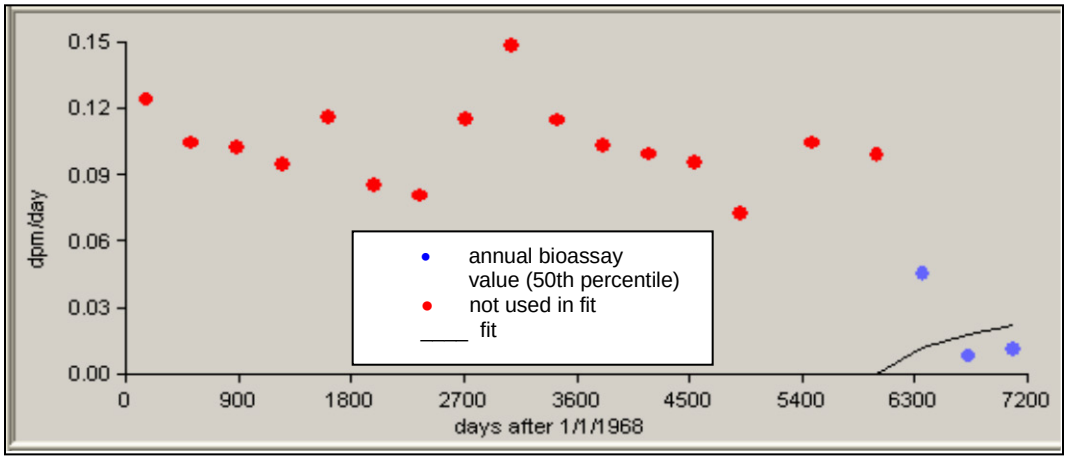

Figure A-34. Assumed ^{241}Am intake, 1985 to 1988, 50th-percentile results, type M.

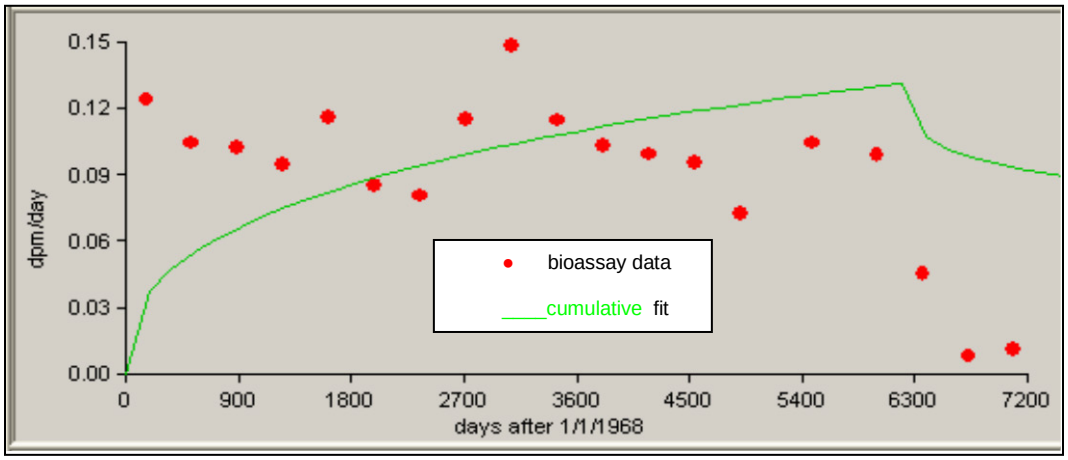

Figure A-35. Predicted cumulative ^{241}Am intake, 1968 to 1988, 50th-percentile composite results, type M.