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ACRONYMS AND ABBREVIATIONS

dpm	disintegrations per minute
DTPA	diethylenetriaminepentaacetic acid
GM	geometric mean
GSD	geometric standard deviation
HERB	Health-Related Energy Research Branch
hr	hour
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
L	liter
m	meter
MDA	minimum detectable activity
ml	milliliter
MPBB	maximum permissible body burden
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
pCi	picocurie
PoC	Probability of Causation
PNNL	Pacific Northwest National Laboratory
PUREX	plutonium–uranium extraction
REX	Hanford Radiological Exposure Records Database
TIB	technical information bulletin
yr	year
U.S.C.	United States Code
µCi	microcurie
µg	microgram
µm	micrometer

1.0 INTRODUCTION

Technical information bulletins (TIBs) are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained. TIBs may be used to assist the National Institute for Occupational Safety and Health (NIOSH) 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 facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. Sections 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 U.S. Department of Energy facility. In addition, there are incidents in which an employee's monitoring records are incomplete or unavailable. In such cases, data from coworkers can be used to approximate an individual's possible exposure. The purpose of this document is to provide the details of the calculation and assignment of intakes based on coworker data from the Hanford site [including the Pacific Northwest National Laboratory (PNNL)] for the purpose of estimating unmonitored exposures.

3.0 OVERVIEW

Analysis of Coworker Bioassay Data for Internal Dose Assignment (ORAUT 2005a) describes the general process for analyzing bioassay data for the assignment of doses based on coworker results.

Bioassay results for Hanford were obtained as a copy of the Hanford Radiological Exposure Records (REX) database sent to the NIOSH Health-Related Energy Research Branch (HERB) before the start of the dose reconstruction project. The REX data needed to generate the bioassay statistics for the coworker data project were converted to Microsoft Access database tables. Data in these tables were spot-checked against REX at Hanford, and no discrepancies were found.

As is typical of a site with large operating reactors and spent fuel dissolution operations, there was potential for exposure at Hanford to many radionuclides including fission and activation products, plutonium, uranium, and tritium. In addition, Hanford handled thorium for part of its history. With the advent of *in vivo* counting, detection of a wide range of gamma-emitting fission and activation products became possible. In addition, bioassay monitoring of workers on small-scale or short-term projects for unusual radionuclides was performed at different times. Therefore, there are a number of different radionuclides in the excreta and *in vivo* data. For most of the radionuclides in the database, there were too few measurements made or too few detections (in the case of *in vivo* measurements) to allow reliable statistical evaluation. Exposure to such radionuclides was arguably rare or limited to only a few workers on a specific project and would not be appropriate to this general coworker study.

The urinalysis data chosen for this coworker study because of general applicability and number of measurements were from plutonium, uranium, radiostrontium, and promethium analyses, although the ^{147}Pm intakes have limited applicability (Sections 4.1.4 and 6.1.4). Before whole-body counting became routine in 1960, bioassay monitoring for intakes of some fission products was performed using a radiochemical procedure called *fission product urinalysis*. This procedure involves chemical separation and counting (gross beta) of rare-earth fission products and radioisotopes of strontium.

However, the results are difficult to interpret because the actual radionuclide or composition of the mixture of radionuclides in the urine was not determined and because different radionuclides had different chemical yields and detection efficiencies. Therefore, intakes of ^{24}Na, ^{65}Zn, ^{90}Sr, and ^{137}Cs were extrapolated from periods when they were measured, and other fission products were accounted for using air concentration limits (Section 6.0).

With the exception of naturally-occurring ^{40}K, only three gamma-emitting radionuclides measured by whole-body counting were routinely reported: ^{137}Cs, ^{24}Na, and ^{65}Zn. The available documentation does not state the reasons for choosing these three radionuclides. Other fission or activation products were reported only when detected above a certain level of significance determined through different methods at different times. A review of the *in vivo* database showed that there was enough data to warrant statistical evaluation only for these three routinely reported radionuclides.

Dose from intakes of tritium was treated as external dose until about 1986 and was reported as part of penetrating dose in the radiological records. Dose from tritium was included in the coworker analysis of penetrating external dose (ORAUT 2005b) and was therefore not duplicated in this coworker analysis.

The statistical analyses of the bioassay data for each radionuclide were performed in accordance with ORAUT (2005a). 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 seven radionuclides at the 50th- and 84th-percentile values was performed to obtain intake rates for assignment of dose distributions.

4.0 DATA

4.1 SELECTED BIOASSAY DATA

Data for each of the electronic database codes considered were extracted from a series of Microsoft Access files that contained a version of the HERB database.

Throughout most of Hanford's history, bioassay data were truncated or censored below some level. Various terms can be applied to such a level, such as *detection limit*, *less-than level*, *reporting level*, *lower limit of detection*, *decision level* or *minimum detectable activity* (MDA). In this document, *reporting level* denotes the level below which a measurement was not recorded. Decision level and MDA, as best as could be determined from available documentation, are used in accordance with the definitions in Health Physics Society Standard N13.30 (HPS 1996). The analysis established time intervals for which single values for the 50th- and 84th-percentile values were calculated. These intervals were determined such that there was a sufficient total number of measurements and a sufficient number of measurements greater than the reporting level to perform meaningful statistics.

For some data, reporting levels were not used for all samples, and there was therefore a large batch of samples at or just above the reporting level, a smattering of samples below the reporting level, and some samples with zero, blank, or null values. This mix of reporting practices led to poor curve fits when values at the reporting level were treated as zeros. Therefore, this analysis used the linear distribution (ORAUT 2005a) for values considered to represent nondetections. The following radionuclide-specific sections discuss exceptions to this treatment.

4.1.1 Plutonium Urinalysis

Routine urinalysis for plutonium at Hanford began in 1946. Over the years, several factors in the methods for measuring and reporting plutonium urinalysis data changed:

- Chemical method
- Radioactivity counting method
- Reporting units
- Reporting levels and data censoring (that is, not reported below a certain activity)
- Method for indicating data below the reporting level
- Consistency of use of the previous two protocols (the data for some years show that the reporting level was not used consistently and/or that different methods of reporting data below the reporting level were used)

Some of these changes affected how the urinalysis data were treated for the statistical analysis. The issues and resolutions are discussed in the following paragraphs.

From 1946 to the third quarter of 1983, plutonium urinalysis results were measured and recorded as a gross alpha count on a chemically separated sample. The measured result was the total activity of ^{238}Pu, ^{239}Pu, and ^{240}Pu but did not include ^{241}Pu nor ^{241}Am. Since the fourth quarter of 1983, the chemically separated sample was measured by alpha spectrometry (for routine and priority samples). The recorded results were a value for ^{239}Pu that was actually the total activity of ^{239}Pu and ^{240}Pu and a value for the ^{238}Pu activity. The statistical analyses were conducted on the total plutonium alpha activity for 1946 to September 1983 and on the $^{239+240}$Pu activity for October 1983 to 1988. Because most plutonium exposures at Hanford would have involved a mixture of isotopes, the results of these different measurement techniques were normalized (Section 5).

Routine plutonium urinalysis samples were usually simulated 24-hr samples, which were collected over two 12-hr periods (usually consecutive evenings). Some samples were not 24-hr samples, especially those collected shortly after a suspected acute intake. The collected volume of urine was part of the record starting partly in 1958 and consistently in 1959, so the 1959 to 1988 results with volumes of less than 400 ml were not used in the statistics. This criterion removed some of the incident samples and some samples from persons who did not follow instructions and provided less than simulated 24-hr samples.

Incident samples were problematic for performing group statistics. Hanford generally collected many samples from a worker involved with a known large acute intake, which were referred to as special or follow-up samples. The number of samples varied depending on the severity of the intake, whether treatment was involved, the willingness of the exposed worker, and general internal dosimetry practices at the time. However, in many cases the number of follow-up samples ranged from tens to hundreds. These samples were not comparable to routine annual or semiannual samples from the majority of the workforce, and they tended to bias the statistics on the high side. It was too difficult to remove all of these samples from the database, and minor acute intakes were frequent enough at Hanford that they could represent the normal course of exposure to plutonium workers. However:

- If there were a large number of samples from a single worker, usually bunched after a specific time, these were removed. A specific number was not rigorously applied as the definition of large, but it was generally greater than about 20 in 1 yr. In addition, once a person was selected to be removed, data for subsequent years in that worker's history were removed until the excretion was near or less than the reporting level.

- If a record of an acute intake was judged to be unrepresentative, that record was removed. Any intake treated by diethylenetriaminepentaacetic acid (DTPA) met this criteria because DTPA-treated urinary excretion is enhanced. Intake through a wound or the skin was considered unrepresentative. Inhalations, however, were considered representative unless they were caused by an event judged to be unrepresentative, such as explosion, fire, or major contamination spread.

Another challenge to data interpretation was results listed as "PU" or "PU239" with blank quantities. For most years, the meaning of a blank was not found in documentation. However, the meaning could be inferred from the number of blank results and how they fit with the other data for the year. For instance, there were many blank results each year in the early years, and it was inferred that the blanks meant a sample was analyzed and nothing was detected. In later years there were many sample results recorded exactly at the recording level but just a few blanks. It was claimant-favorable to leave out the blanks in those years under the assumption that a blank was a sample collected for which the analysis failed in some way. Each year's distribution of sample results was scrutinized, and instructions were written on how to disposition blank results on a year-by-year basis.

The method used to indicate no detection of plutonium, similar to the issue of blanks, varied over time and appeared not to be consistent even during a given period. For instance, zero, blank, and the reporting level were apparently used to indicate nondetections during some periods. In general, Hanford used reporting levels for plutonium urinalysis results until September 1981. Whether a value recorded at the reporting level meant no detection, or whether the reporting level or higher was a true detection and nondetections were recorded as zero or blank, was indeterminate at the broad level.

The meanings of the reporting level, zero, and blanks had to be determined on a year-by-year basis, and the decision was included in the specific instructions on how to rank such sample results. For example, the 1966 to 1974 reporting level was 1.1×10^{-8} µCi/sample (0.244 dpm/sample) and the 1975 to 1981 reporting level was 0.025 dpm/sample. These numbers were considered to be one-half of the detection level and were used to indicate no detection of plutonium. The linear distribution was used to distribute and rank blanks, zeros, and values at these reporting levels. For other years, however, the reporting level was less apparent because there were many values that were probably a reporting level, but other values were less than the reporting level. The latter samples were included in the linear fit, and the apparent reporting level was set as the top of the linear distribution.

The following were set as the top of the linear distribution:

1946	3.6E-7 µCi/sample
1947–1948	3.0E-7 µCi/sample
1949–1951	1.5E-7 µCi/sample
1952	8.1E-8 µCi/sample
1953–1957	2.3E-8 µCi/sample
1958–1965	1.2E-8 µCi/sample
1966–1974	1.1E-8 µCi/sample
1975–Sept. 9, 1981	0.025 dpm/sample

On September 10, 1981, the recording practice changed from recording 0.025 dpm/sample to indicate a nondetection to recording the exact result as measured. After September 9, 1981, therefore, any result greater than zero was used as recorded. Zero and negative results were included in the ranking of samples but not in the fitting of the line. The linear distribution was not used for data after September 9, 1981.

Units for plutonium analyses in the Hanford records were microcuries per sample from 1946 to 1974 and disintegrations per minute per sample from 1975 to present. The earlier values were converted to disintegrations per minute before statistical analysis.

The time interval for separate statistical analyses varied. The choice of the interval was based on the number of results versus the number of results over the reporting level. If there were several hundred sample results and 10% or more exceeded the reporting level, the basic time interval was quarterly. Table 4-1 lists the intervals. The unusual division of the third and fourth quarters of 1981 was applied because of the change in recording practice discussed above.

Table 4-1. Time intervals for statistical analysis of plutonium urine samples.

Calendar year	Analysis interval
1946	Year
1947	Year
1948	Half years
1949	Year
1950	Year
1951	Year
1952	Year
1953	Half years
1954–Jun. 1981	Quarter years
3Q 1981	Jul. 1-Sep. 9
4Q 1981	Sep. 10-Dec. 31
1982–1988	Quarter years

4.1.2 Uranium Urinalysis

Routine urinalysis for uranium began in 1947, but the results were considered unreliable until improvements in the procedure were made (Healy 1948). The 1947 data were analyzed but not used for intake modeling. Data analyzed for this study were from elemental analysis procedures. Starting in 1983 an alpha spectrometry procedure has been used for some workers, but these data were less robust and were not representative of the overall Hanford workforce. The results were recorded as micrograms per liter from 1947 to July 1, 1982, and as micrograms per sample from July 2, 1982, to present. The latter were converted to micrograms per liter using the sample volume recorded as part of the information in the database. Elemental uranium samples were not usually 24-hr samples; a mix of sample collection periods was used from 1947 to 1988 with overnight sampling being one of the more frequent methods. Therefore, samples of less than 400 ml were not removed from the uranium data.

In general, Hanford did not have many large, acute intakes of uranium; only six samples were removed because they were collected after unusual acute intakes (e.g., a worker fell into a vat of uranyl nitrate).

A small number of duplicate entries were found in the records from 1965 and 1968 that were true duplicates rather than, for instance, two analyses of the same sample; one of each pair was removed from the data before statistical analysis.

Reporting levels are shown below.

1948–74	4.0 µg/L
1975–81	0.4 µg/L

1982 to present	Actual values were recorded as measured.

Use of the reporting levels for uranium urinalysis appears to have been more consistent than was the case for plutonium, with the exception of one period. From 1958 to 1966 there were many results lower than 4 µg/L. It is not known if these indicated detection (i.e., whether the MDA was really reduced during this period). Therefore, these were treated as less-than results and included in the linear distribution. In 1967, Hanford returned to consistent use of the 4 µg/L reporting level.

Through 1981, zeros, blanks, or less-than results were treated as nondetections and included in the linear distribution. Starting in 1982,

- No reporting level was used.
- The linear distribution was not used in the statistical analysis.
- Blanks were considered invalid samples and not used in the statistical analysis.
- Zero and negative numbers were included in the ranking of samples but not in the fitting of the line.

Table 4-2 lists the time intervals for separate statistical analyses. The Plutonium–Uranium Extraction (PUREX) and UO3 plants were shut down during the 1970s, so there were few exposures and few samples. There were only 65 samples collected in 1973; the results were comparable to neighboring years, so the 1973 statistical parameters were included.

Table 4-2. Time intervals for statistical analysis of uranium urine samples.

Calendar year	Analysis interval
1947	Year
1948	Half years
1949–1969	Quarter years
1970–1983	Year
1984–1988	Quarter years

4.1.3 Strontium Urinalysis

Specific urinalysis for radiostrontium began in 1965. Before that, the fission product urinalysis method was used to monitor for radiostrontium and some other fission product radionuclides. Both ^{89}Sr and ^{90}Sr could have been counted depending on whether the sample was beta-counted before or after a period for ingrowth of ^{90}Y. For this study, all the results were assumed to be ^{90}Sr because it was generally more prevalent and because it produces higher (more claimant-favorable) doses per unit intake than ^{89}Sr. Results were recorded as microcuries per liter for 1965 to 1974 and as disintegrations per minute per sample from 1975 to the present. The earlier results were converted to disintegrations per minute per sample before statistical analysis using the recorded volume of the sample.

Most strontium urine samples were simulated 24-hr samples, so samples that were less than 400 ml were removed from the data before statistical analysis. Thirteen sample results were removed because they were follow-up samples to known large acute intakes; one sample result was removed because it was a recount. There were some obvious duplicates that were removed.

Reporting levels are shown below.

1965–1969	1.67E-5 µCi//L
1970–1974	1.00E-6 µCi/L
1975–3/1979	2 dpm/sample
4/1979–1981	5 dpm/sample
1982–1988	Actual values were recorded as measured

Blanks with volumes greater than 400 ml were rare; these were considered invalid and were not used. Through 1981, zero or less-than results were treated as nondetections and included in the linear distribution. Starting in 1982:

- No reporting level was used.
- The linear distribution was not used in this analysis.
- Zero and negative numbers were included in the ranking of samples but not in the fitting of the line.

Table 4-3 lists the time intervals for separate statistical analyses. Before 1970 there were few samples in a given year and very few samples that exceeded the reporting level, so samples were grouped into two 3-yr intervals. Before 1979, in general, there were only a few hundred (and sometimes less than a hundred) samples in a year. Whole-body counting was the primary bioassay method for fission products; the exception was for the workers at the Waste Encapsulation and Storage Facility where exposure to pure ^{90}Sr was possible. The data from 1979 were split into two periods because of the change in reporting level from 2 to 5 dpm/sample on April 1.

Table 4-3. Time intervals for statistical analysis of ^{90}Sr urine samples.

Calendar year	Analysis interval
1965, 1966, 1967	As one group
1968, 1969, 1970	As one group
1971–1978	Years
1Q 1979	Quarter
2,3,4Q 1979	As one group
1980–1981	Years
1982–1988	Quarters

4.1.4 Promethium Urinalysis

Promethium-147 is a fission product with greater abundance in 1-yr-aged fuel (1 yr since removal from the reactor) in weapons-grade fuel than either ^{90}Sr or ^{137}Cs. However, it behaves in the body somewhat similarly to ^{90}Sr and had an early maximum permissible body burden (MPBB) that was a factor of 30 (ICRP 1959) less than that for ^{90}Sr and, later, an annual limit on intake that was a factor of 14 (ICRP 1979, 1981) less than that for ^{90}Sr. The presence of ^{147}Pm would have been detected as part of the fission product urinalysis even though the results of the fission product urinalysis were calibrated for and interpreted as ^{90}Sr. When whole-body counting and ^{90}Sr urinalysis replaced the fission product urinalysis as the bioassay method of choice for fission products, ^{147}Pm was considered an insignificant contributor to internal dose and ^{147}Pm bioassay for workers exposed to general fission products was not performed. Promethium-147 as an unconcentrated fission product in general contamination is treated as a miscellaneous fission product as described in Section 6.8.

Specific bioassay for ^{147}Pm was initiated when the Pacific Northwest Laboratory (now PNNL) began manufacturing ^{147}Pm heat sources in the 325 Building in 1966. Some exposure to ^{147}Pm also occurred in the 308 Fuels Laboratory. The number of workers in the bioassay program and the number of samples were small in comparison to the numbers for the plutonium, uranium, or strontium bioassays, with a high of 65 workers in 1968. There was almost no sampling from 1972 to 1975, which probably indicates a cessation of the original heat source program, and only 20 workers were sampled from 1976 to 1979. The exact end date of the heat source program has not been determined. For purposes of this study, it was assumed that exposure occurred from 1966 to 1979, although it is likely that any exposure from 1972 to 1975 was only due to residual activity.

Results were recorded as microcuries per liter from 1966 to 1974 and as disintegrations per minute per sample from 1975 to 1979. The earlier results were converted to disintegrations per minute per sample using the sample volume.

Most routine samples were simulated 24-hr samples, so samples with volumes smaller than 400 ml were removed from the data before statistical analysis. There were a large number of duplicate entries in the database from 1966 to 1968, and these were removed. There was a glovebox rupture and large contamination spread that mainly affected three workers in 1967, and an overpressurization and blowback of a sampling line affected another worker in 1968; samples associated with these incidents were removed.

Reporting levels are shown below.

1966–Mar. 25, 1970	1.67E-5 µCi/L
Mar. 31, 1970–1974	1.00E-5 µCi/L
1975–1979	25 dpm/sample

The linear distribution was applied to results at or below the reporting levels. There were no blanks with volumes greater than 400 ml.

Table 4-4 lists the time intervals for separate statistical analyses. The split in 1970 occurred because of the change in reporting level on March 31.

Table 4-4. Time intervals for statistical analysis of ^{147}Pm urine samples.

Calendar year	Analysis interval
1966, 1967	As one group
1968, 1969, 1970 (through March 25,1970)	As one group
Mar. 31–Dec. 31, 1970; 1971	As one group
1972–1974	Not enough samples for statistics
1975, 1976, 1977, 1978, 1979	As one group

4.1.5 Zinc-65 in Whole-Body Counts

Zinc-65 was routinely reported in whole-body counts from 1960 to 1983. There were only about 370 recordings of ^{65}Zn in whole-body counts in 1984, but that was considered sufficient to include in the statistical analysis. After 1984 there were very few detections of ^{65}Zn in whole-body counts. Zinc-65 was mostly a concern during the operation of the once-through-cooled reactors (through 1971) when large activities of ^{65}Zn were discharged to the Columbia River.

The three largest local cities drew their sanitary water mostly from the Columbia River, as did the reactors on the site. Brady (1964) shows that ^{65}Zn passed through the purification systems in sufficient concentration to produce measurable body burdens in many Hanford workers. Brady also

attributed some of the ^{65}Zn to ingestion of fish from the Columbia River or from crops irrigated by Columbia River water.

Figure A-23 shows a decrease in the median body burden of ^{65}Zn starting in 1972 (with the exception of a spike in body burden in the fourth quarter of 1976), which appears to show the effect of the shutdown of the once-through-cooled reactors. However, it was apparent from the distribution of activities measured in the workers that inhalation in the workplace also had to be a viable intake pathway; ingestion of water cannot explain the higher body burdens at the higher percentile values of the quarterly distributions. Therefore, both inhalation and ingestion pathways were modeled.

All whole-body counts were recorded in nanocuries.

In whole-body counting, the decision level varies with every individual and every count because of the interperson variability in activity of ^{40}K, the intraperson variability in activity of interfering radionuclides a person could have on them on any given day (especially radon and thoron progeny), and the day-to-day variability in the natural background in the counting cell. In addition and especially during the early years of the *in vivo* counting program, there were improvements to the program including type or number of detectors, counting times, and improved electronics. It was common for more than one whole-body counting system to be used at a time. Therefore, the stated detection limits were approximate and were meant to apply to a general range; little documentation on detection levels has been found. A single reporting level is not apparent in the recorded data.

Because of these factors, it was impossible to state a distinct threshold value above which all results meant detection and below which all results meant nondetection. For 1960 to 1974, a detection level of 0.8 nCi for ^{65}Zn was found in the documentation. Relative to the distribution of results in most years, this value was a reasonable one to use as the reporting level. Blanks and zero results were distributed using the linear distribution with 0.8 nCi as the upper range; values between zero and 0.79 nCi were used as recorded and mixed in with the numbers from the distribution.

For 1975 to 1984, the value of 0.75 nCi was distinctly used as the reporting level, with only one value that fell between zero and 0.75 nCi. Blanks and zeros were distributed using the linear distribution.

Table 4-5 lists the time intervals for separate statistical analyses.

Table 4-5. Time intervals for statistical analysis of ^{65}Zn whole-body counts.

Calendar year	Analysis interval
1960	Year
1961–1962	Half years
1963–1974	Quarter years
1975	Half years
1976–1983	Quarter years
1984	Year

4.1.6 Sodium-24 in Whole-Body Counts

Similar to ^{65}Zn, ^{24}Na was reported routinely from 1960 to 1983 with a significant but much smaller number of results in 1984; after 1984 there were very few recorded results. Sodium-24 was released to the Columbia River from the once-through-cooled reactors, but its short half-life (15 hr) prevented significant concentrations in local municipal drinking water systems. Its presence was correlated with reactor workers and was to some extent believed to be due to drinking water at the reactors (Brady 1964). However, as with ^{65}Zn there were body burdens that were too high to be explained by

ingestion of drinking water. As a consequence, ^{24}Na was modeled using both inhalation and ingestion pathways.

As explained in the ^{65}Zn section, a distinct threshold value for detection was not apparent from the data. For 1960 the lowest reported value was 0.56 nCi, so this value was used as the reporting level. Blanks and zero results were distributed using the linear distribution with 0.56 nCi as the upper range. For 1961 to 1974, a detection level of 0.3 nCi for ^{24}Na was found in the documentation. This value was reasonable for use as the reporting level even though there were many results recorded at smaller values. Blanks and zero results were distributed using the linear distribution with 0.3 nCi as the upper range. Values between zero and 0.29 nCi were used as recorded and mixed with the numbers from the distribution. For 1975 to 1984, a value of 0.31 nCi was distinctly being used as the reporting level with no measurements recorded lower than 0.31 nCi. Blanks and zeros were distributed using the distribution with 0.3 nCi as the upper range.

Table 4-6 lists the time intervals for separate statistical analyses.

Table 4-6. Time intervals for statistical analysis of ^{24}Na whole-body counts.

Calendar year	Analysis interval
1960	Year
1961–1962	Half years
1963–1983	Quarter years
1984	Half years

4.1.7 Cesium-137 in Whole-Body Counts

Cesium-137 was recorded routinely with every whole-body count from 1960 to 1983. For 1984 to 1988, ^{137}Cs was generally recorded only if it was detected above a reporting level, but the database also shows valid whole-body counts including blank values for ^{137}Cs. Why this occurred is not known. Because of its long half-life and abundance in the waste from the separations plants, ^{137}Cs has long been considered one of the principal contaminants at Hanford and has often been used as an indicator of potential intakes.

For 1960 to 1974, a detection level of 0.5 nCi for was found in the documentation, but it is clear from the distribution of results that no distinct reporting level was used. Therefore, the distribution for each year was evaluated, and a value was chosen as the upper range of the linear distribution for assignment of blanks and zeroes. This value was chosen as 1) being reasonable in relation to the stated detection limit and 2) representing a break point in the pattern of results when ranked from highest to lowest (with only a few scattered results showing below the breakpoint).

Table 4-7 lists these values. For each year, values between zero and the value given in Table 4-7 were used as recorded and mixed with the distribution of the blank and zero results. Starting in 1976, 0.66 nCi was the stated detection level in the database and its use as a reporting level was clear. From June 14, 1986, to September 19, 1986, the stated reporting level varied with each count but ranged mostly between 1 and 2 nCi. On September 22, 1986, a reporting level of 3 nCi was implemented and remained in effect until some time after 1988.

Table 4-7. Subjective upper range for the linear distribution.

Calendar year	Upper range of the distribution (nCi)
1960–1962	1.0

1963–1964	1.4
1965–1966	1.5
1967–1968	1.0
1969–Jun. 1986	0.65
Jul. 1986–1988	3.0

Table 4-8 lists the time intervals for separate statistical analyses.

Table 4-8. Time intervals for statistical analysis of ^{137}Cs whole-body counts.

Calendar year	Analysis interval
1960–1974	Quarter years
1975	Only two values reported and neither above the reporting level. This year was skipped.
1976–1983	Quarter years
1984–1988	Half years

When the distributions for the 1960s with the linear distributions were plotted and fitted, it became apparent both visually and from the R^2 values that the linear distribution for the blanks and zeros did not match well with the distribution of the ^{137}Cs results above the detection level. As a consequence, the method of including zeros and blanks in the ranking but not the fitting (used for coworker data for Y-12, Oak Ridge National Laboratory, K-25, and Portsmouth sites) was applied to each data set. The two methods were compared for each time interval. In general through 1983, the second method (rank-only method) provided better results in relation to three criteria: 1) the R^2 fit parameter, 2) a subjective visual inspection, and 3) comparison of the fitted values for the 50th-and 84th-percentile values versus the same values in the ranked, unfitted raw data. Table 4-9 lists the latter comparisons. The shaded cells highlight the method that provided the closest fit to the raw data.

The ^{137}Cs data could have been unusual in that all workers had body burdens of ^{137}Cs due to fallout from nuclear weapons testing, and the few whole-body counts that were recorded as zero or blank had true values that were just barely below detection. Distributing these counts linearly between zero and the reporting level, therefore, did not match well with the bulk of the results that were above the reporting level.

From 1984 to June 1986, ^{137}Cs results were recorded differently than in other years. When ^{137}Cs was not detected, the radionuclide was sometimes listed in the results as a blank but, more often, ^{137}Cs was not listed at all. Instead, it was treated like the many other fission product radionuclides that could be detected by *in vivo* counting but are not listed if they are not detected. For this period the total number of whole-body counts given was determined by tallying the number of ^{40}K counts, which were recorded for every valid whole-body count. Each whole-body count for which ^{137}Cs was not listed was considered the same as a whole-body count with a blank or zero result for ^{137}Cs.

From 1984 to 1988, the rank-only method did not provide good fits. This was due in part to inconsistent use of the supposed 0.65-nCi reporting level, which could have been due to the use of three different whole-body detectors. For example, Cunningham (1984) stated, “The normal detection limit of two nanocuries was increased to five nanocuries at the UNC’s [a Hanford contractor at that time] request for whole-body counts performed at the portable whole-body counter during December

Table 4-9. Comparison of ^{137}Cs 50th- and 84th-percentile values between the linear distribution and the rank-but-not-fit methods.

	50th-percentile value					84th-percentile value				
Quarter	Rank only	linear distrib.	Raw data	% difference Rank/raw[a]	% difference Lin./raw[a]	Rank only	linear distrib.	Raw data	% difference Rank/raw[a]	% difference Lin./raw[a]
02/15/1960	6.773	6.7049	7.100	-5	-6	9.620	9.7916	9.440	2	4
05/15/1960	6.689	6.3078	7.000	-4	-10	9.347	10.0704	8.900	5	13
08/15/1960	5.977	5.0141	6.250	-4	-20	9.466	11.0653	9.000	5	23
11/15/1960	5.770	4.8916	6.100	-5	-20	8.302	9.7426	8.100	2	20
02/15/1961	4.728	3.5971	4.950	-4	-27	6.858	8.3604	6.800	1	23
05/15/1961	4.482	4.0306	4.550	-1	-11	6.764	7.5645	6.544	3	16
08/15/1961	3.805	3.4611	4.000	-5	-13	6.006	6.6417	5.900	2	13
11/15/1961	3.491	3.2782	3.700	-6	-11	5.184	5.5648	4.940	5	13
02/15/1962	3.527	2.7622	3.700	-5	-25	5.563	6.6115	5.588	0	18
05/15/1962	3.457	2.8695	3.400	2	-16	5.055	5.9044	5.124	-1	15
08/15/1962	4.378	3.9146	4.500	-3	-13	6.502	7.3051	6.300	3	16
11/15/1962	5.253	4.5092	5.300	-1	-15	7.678	8.8681	8.100	-5	9
02/15/1963	6.691	6.4816	6.900	-3	-6	10.362	10.7872	9.764	6	10
05/15/1963	8.922	8.4766	9.100	-2	-7	13.998	14.9786	13.000	8	15
08/15/1963	11.218	10.7314	11.000	2	-2	16.663	17.7776	16.000	4	11
11/15/1963	13.470	11.5633	14.000	-4	-17	19.952	23.5147	19.000	5	24
02/15/1964	15.374	11.5565	17.000	-10	-32	23.543	29.8527	22.000	7	36
05/15/1964	17.644	14.3843	18.500	-5	-22	26.857	32.8181	27.000	-1	22
08/15/1964	18.129	15.6201	19.000	-5	-18	26.767	31.5749	27.000	-1	17
11/15/1964	17.811	15.3452	19.000	-6	-19	28.334	33.3275	26.000	9	28
02/15/1965	15.208	10.3744	17.000	-11	-39	23.287	30.3181	23.000	1	32
05/15/1965	15.288	14.9963	16.000	-4	-6	23.190	23.9664	22.400	4	7
08/15/1965	13.341	10.8838	14.000	-5	-22	19.881	24.1283	19.000	5	27
11/15/1965	11.964	8.8597	13.000	-8	-32	18.931	23.7735	18.000	5	32
02/15/1966	10.544	7.9454	12.000	-12	-34	16.593	20.5504	16.000	4	28
05/15/1966	8.526	7.0335	9.300	-8	-24	13.837	16.4036	13.000	6	26
08/15/1966	8.198	8.0457	8.700	-6	-8	13.210	13.6153	12.000	10	13
11/15/1966	6.417	5.2622	7.200	-11	-27	12.039	14.0325	11.000	9	28
02/15/1967	5.877	5.4974	6.300	-7	-13	9.856	10.7179	9.644	2	11
05/15/1967	5.417	4.8662	5.800	-7	-16	9.242	10.3839	9.000	3	15
08/15/1967	4.770	4.1398	5.300	-10	-22	8.025	9.1841	7.900	2	16
11/15/1967	4.049	3.1439	4.700	-14	-33	7.580	8.9436	6.900	10	30
02/15/1968	3.195	1.9707	3.500	-9	-44	6.012	6.9889	6.000	0	16
05/15/1968	2.574	2.1498	3.000	-14	-28	4.939	5.5300	4.740	4	17
08/15/1968	2.667	2.0480	3.000	-11	-32	5.467	6.2850	5.260	4	19
11/15/1968	2.824	2.3593	3.100	-9	-24	5.511	6.2571	5.100	8	23
02/15/1969	3.022	2.3924	3.300	-8	-28	5.516	6.5052	5.200	6	25
05/15/1969	2.176	1.7451	2.400	-9	-27	4.728	5.3988	4.300	10	26
08/15/1969	2.222	1.6440	2.400	-7	-31	4.332	5.0581	4.300	1	18
11/15/1969	2.354	1.4820	2.550	-8	-42	5.610	6.3480	4.700	19	35
02/15/1970	2.302	1.5264	2.500	-8	-39	4.695	5.1308	4.400	7	17
05/15/1970	2.074	1.6764	2.300	-10	-27	4.580	5.2044	3.900	17	33
08/15/1970	2.152	1.6640	2.500	-14	-33	4.536	5.1995	4.100	11	27
11/15/1970	2.642	1.9784	2.900	-9	-32	4.874	5.8021	4.500	8	29
02/15/1971	2.161	1.6815	2.400	-10	-30	4.107	4.7771	4.000	3	19
05/15/1971	2.429	2.1680	2.600	-7	-17	4.501	4.9822	4.168	8	20
08/15/1971	2.527	2.2540	2.600	-3	-13	4.389	4.9210	4.000	10	23
11/15/1971	2.674	2.4173	2.700	-1	-10	4.727	5.2469	4.200	13	25
02/15/1972	2.368	1.9827	2.600	-9	-24	4.295	4.9311	4.000	7	23
05/15/1972	2.324	2.1229	2.500	-7	-15	4.995	5.4094	4.200	19	29
08/15/1972	2.325	2.1214	2.400	-3	-12	4.530	4.9716	4.000	13	24
11/15/1972	2.200	1.7517	2.500	-12	-30	5.052	5.7898	4.400	15	32
02/15/1973	2.054	1.6426	2.300	-11	-29	4.504	5.1906	3.900	15	33
05/15/1973	1.848	1.5758	2.000	-8	-21	3.468	3.9319	3.300	5	19
08/15/1973	1.830	1.5869	2.000	-9	-21	3.345	3.7805	3.300	1	15
11/15/1973	1.640	1.3787	1.800	-9	-23	3.300	3.7405	3.000	10	25
02/15/1974	1.251	1.0530	1.400	-11	-25	3.020	3.3523	2.700	12	24
05/15/1974	0.919	0.7600	0.945	-3	-20	2.184	2.4080	2.100	4	15
08/15/1974	1.089	0.9004	1.100	-1	-18	2.462	2.7476	2.400	3	14

Table 4-9. (Continued). Comparison of ^{137}Cs 50th- and 84th-percentile values between the linear distribution and the rank-but-not-fit methods.

	50th-percentile value						84th-percentile value				
Quarter	Rank only	linear distrib.	Raw data	% difference Rank/raw[a]	% difference Loch/raw[a]		Rank only	linear distrib.	Raw data	% difference Rank/raw[a]	% difference Loch/raw[a]
11/15/1974	1.109	0.9124	1.100	1	-17		2.702	2.9827	2.600	4	15
02/15/1976	1.049	0.8155	1.100	-5	-26		2.165	2.4371	2.200	-2	11
05/15/1976	1.120	0.9374	1.200	-7	-22		2.695	2.9798	2.300	17	30
08/15/1976	0.932	0.7885	0.970	-4	-19		2.182	2.4143	2.100	4	15
11/15/1976	1.618	1.3848	1.700	-5	-19		3.974	4.4145	3.700	7	19
02/15/1977	1.365	1.0991	1.400	-2	-21		2.988	3.3717	2.900	3	16
05/15/1977	1.469	1.2989	1.500	-2	-13		3.426	3.7779	2.800	22	35
08/15/1977	1.122	0.9515	1.200	-7	-21		2.924	3.2178	2.600	12	24
11/15/1977	0.868	0.7054	0.785	11	-10		2.247	2.4277	2.220	1	9
02/15/1978	1.052	0.8522	1.100	-4	-23		2.643	2.9030	2.500	6	16
05/15/1978	0.788	0.7319	0.860	-8	-15		2.380	2.5618	2.100	13	22
08/15/1978	0.779	0.6937	0.800	-3	-13		2.234	2.4145	2.100	6	15
11/15/1978	1.082	0.8820	1.100	-2	-20		2.681	2.9578	2.600	3	14
02/15/1979	1.178	1.0128	1.300	-9	-22		2.958	3.2641	2.700	10	21
05/15/1979	0.867	0.6959	0.840	3	-17		2.052	2.2602	2.100	-2	8
08/15/1979	0.922	0.7524	0.940	-2	-20		2.198	2.4296	2.200	0	10
11/15/1979	1.239	0.9935	1.300	-5	-24		2.654	3.0002	2.604	2	15
02/15/1980	1.152	0.9653	1.200	-4	-20		2.820	3.1273	2.700	4	16
05/15/1980	0.818	0.8072	0.880	-7	-8		2.912	3.0825	2.400	21	28
08/15/1980	0.669	0.6006	0.635	5	-5		1.897	2.0524	1.800	5	14
11/15/1980	0.732	0.6364	0.720	2	-12		1.940	2.1137	1.900	2	11
02/15/1981	0.828	0.6995	0.820	1	-15		1.096	2.3033	2.100	0	10
05/15/1981	0.499	0.4194	0.487	3	-14		1.348	1.3065	1.200	-1	9
08/15/1981	0.335	0.3650	0.435	-23	-16		1.247	1.1101	1.000	-5	11
11/15/1981	0.474	0.3995	0.474	0	-16		1.027	1.2101	1.188	-8	2
02/15/1982	0.565	0.4809	0.556	2	-13		1.295	1.4869	1.300	4	14
05/15/1982	0.470	0.4335	0.496	-5	-13		1.124	1.3749	1.300	-4	6
08/15/1982	0.436	0.3836	0.460	-5	-17		0.815	1.1464	1.100	-7	4
11/15/1982	0.532	0.4545	0.521	2	-13		0.905	1.4185	1.300	0	9
02/15/1983	0.426	0.4016	<.65				1.119	1.2493	1.200	-6	4
05/15/1983	0.302	0.3348	<.65				0.02194	0.9809	0.840	-3	17
08/15/1983	0.371	0.3528	<.65				0.06501	1.0379	0.920	-2	13
11/15/1983	0.435	0.3978	<.65				0.02014	1.2350	1.200	-7	3
04/01/1984	0.00080	0.2487	<.65				4.686	0.6537	<.65		
10/01/1984	0.00786	0.2461	<.65				0.00089	0.6285	<.65		
04/01/1985	0.00140	0.2430	<.65				3.781	0.6134	<.65		
10/01/1985	3.785	0.2398	<.65				0.124	0.5927	<.65		
04/01/1986	0.00001	0.2450	<.65				1.075	0.6327	<.65		
10/01/1986	2.786	1.1416	<3.0				0.469	2.7971	<3.0		
04/01/1987	0.0123	1.1220	<3.0				0.152	2.8167	<3.0		
10/01/1987	0.409	1.1235	<3.0				1.096	2.8170	<3.0		
04/01/1988	0.131	1.1169	<3.0				1.348	2.7720	<3.0		
10/01/1988	0.0274	1.1106	<3.0				1.247	2.7455	<3.0		

a. Shaded cells denote which of the two methods was closer to the raw distribution.

1983 at 100-N Area." This implies that the detection limit for the portable whole-body counter was usually 2 nCi, although the letter does not state to which radionuclide that applied. It is possible that the sensitivity for the portable counter was not as good as for the detectors used at the whole-body counting facility. In addition, the sensitivities of the two counters at the fixed facility were not the same (Palmer, Rieksts, and Spitz 1984). Because of the different sensitivities, it is likely that not all counts recorded as blanks for ^{137}Cs were really less than 0.65 nCi. Another reason for the poor fits is that the numbers of results recorded as greater than the reporting level (0.65 nCi for 1984 to September 19, 1986, and 3 nCi for September 22, 1986, to 1988) were very small (generally less than 2% of the total counts during each half-year period). The rank-only method forces a fit to these small numbers of detected results and extrapolates the fits to the almost 4,000 counts in each half-year period that had no detection.

This analysis used the linear distribution for 1984 to 1988 because it provides better fits (visually and by the R^2 values) and is less biased under the circumstances mentioned above.

4.2 ANALYSIS

For each of the seven radionuclides, a lognormal distribution for the data in the intervals specified in Tables 4-1 to 4-6 and Table 4-8 was assumed. The 50th- and 84th-percentile values were calculated using the method described in ORAUT (2005a). Tables A-1 to A-7 in Attachment A show the statistical analysis results for plutonium, uranium, ^{90}Sr, ^{147}Pm, ^{65}Zn, ^{24}Na, and ^{137}Cs.

5.0 INTAKE MODELING

5.1 ASSUMPTIONS

All urinalysis results were assumed to be representative of a full-day (24-hr) urinary excretion or were either eliminated or normalized to be representative of a full day before creating the lognormal plots. Each result used in the intake calculation was assumed to have a normal distribution, and a uniform absolute error of 1 was applied to all results, which weighted all results equally. A chronic exposure pattern was assumed, even though this is unlikely for most exposures at Hanford, because it approximates a series of acute intakes with unknown dates. Intakes were assumed to be from inhalation using a default breathing rate of 1.2 m^3/hr and a 5-µm activity median aerodynamic diameter particle size distribution unless otherwise specified. Intakes of ^{65}Zn and ^{24}Na were determined using whole-body counting results. As discussed in Sections 4.1.5 and 4.1.6, both inhalation and ingestion intakes were possible, so both were modeled.

The results for ^{147}Pm and ^{90}Sr urinalysis were taken directly from the statistical analysis of the database, as were the results for ^{65}Zn, ^{24}Na, and ^{137}Cs whole-body counting.

For plutonium, ^{239}Pu was used for the IMBA intake modeling, but the database results were presumed to be gross plutonium alpha measurements through the third quarter of 1983. To convert from gross plutonium alpha to ^{239}Pu, fresh fuel-grade plutonium was assumed for 1945 to 1949, 5-yr-aged fuel-grade plutonium was assumed for 1950 to 1954, and 10-yr-aged fuel-grade plutonium was assumed for 1955 and after. Table 5-1 lists the percentages of ^{239}Pu used. Starting in October 1, 1983, alpha spectrometry was used in the analysis to specifically identify the ^{239}Pu; therefore, no correction factor was used.

Table 5-1. Plutonium mixture usage.

Time period	Plutonium grade	Percentage ^{239}Pu of plutonium alpha emitters
1946-1949	Fresh fuel-grade	82.4%
1950-1954	5-yr-aged fuel-grade	83.0%
1955-09/30/1983	10-yr-aged fuel-grade	83.5%
10/01/83+	10-yr-aged fuel-grade	100% (isotopic analysis)

For uranium, because the IMBA program requires urine results in units of activity per day, the total uranium values in micrograms per liter were multiplied by 1.4 to normalize them to the Reference Man excretion rate of 1,400 ml/d. Because a variety of enrichments was possible, the intake modeling used mass concentration units and ^{234}U was assumed for all the IMBA intake modeling. This did not affect the data fits for intake determination (i.e., the same total intakes would be obtained for any enrichment that was assumed) because all uranium isotopes have the same biokinetic behavior and the isotopes considered in this analysis have long half-lives relative to the assumed intake period.

To convert to units of activity for dose calculation, the 0.7054 pCi/µg specific activity of natural uranium was assumed through 1952, and the 0.9099 pCi/µg specific activity of recycled uranium was used for later years (ORAUT 2004). Like the intake modeling, ^{234}U was used to calculate the doses. The ICRP Publication 68 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 (ICRP 1993). Because of the isotopic compositions of the source terms, the ^{234}U dose conversion factor yields claimant-favorable doses.

5.2 BIOASSAY FITTING

The IMBA computer program was used to fit the bioassay results to a series of chronic inhalation or ingestion intakes. The exception is that one acute intake was used in the modeling of ^{24}Na exposure because that resulted in the best fit. Modeling was performed only for intervals when data were available. Having been based on whole-body counts, the data for ^{65}Zn and ^{24}Na were available for 1960 to 1984. The least amount of available data was for ^{147}Pm from 1966 to 1979. Plutonium data was from 1946 to 1988, uranium data was from 1948 to 1988, and ^{90}Sr data was from 1965 to 1988.

The intake assumptions were based on observed patterns in the bioassay data. Intervals with constant chronic intake rates were chosen by selecting periods during which the bioassay results were of similar magnitudes. A new chronic intake period was started where the data indicated a significant sustained change in the results.

5.3 RADIONUCLIDES AND MATERIAL TYPES

For each considered radionuclide or group of radionuclides, the bioassay results were entered into IMBA with assumed material types in terms of lung absorption type or uptake factor from the gastrointestinal tract. The types were chosen to be consistent with International Commission on Radiological Protection (ICRP) Publication 68 (ICRP 1993) and the Hanford internal dosimetry technical basis document (ORAUT 2004). Attachment A shows the resultant 50th-percentile intakes as plots. The annual bioassay data used in the fits are shown as solid blue dots (●) (dark spots when printed), and data that are not used in the fits are shown as red dots (●) (light dots when printed).

The type S compounds present at Hanford have very long radiological half-lives, and the materials are retained in the body for long periods. Therefore, the excretion results for different chronic intake periods are not independent for type S materials. For example, an intake in the 1950s could contribute to urinary excretion in the 1980s and later. To avoid potential underestimation of intakes for people who worked at Hanford for relatively short periods, each chronic intake of type S material was independently fit using only the bioassay results from the single intake period. This same process was used for type M plutonium and ^{147}Pm as well. This method likely results in an overestimate of intakes, particularly for assumed type S exposures extending through multiple assumed intake periods. However, this approach was not used for type S plutonium. See Section 6.1 for an explanation on how to use the type S plutonium intake.

5.3.1 Plutonium

Both type M and S materials were present at Hanford and were common enough to apply to general workers, hence, both types were modeled. Tables 5-2 and 5-3 provide intakes for $^{239+240}$Pu. Dose reconstructions must also include intakes of other plutonium isotopes and ^{241}Am as shown in Table 5-1.

5.3.1.1 Type M

This section shows intakes when the plutonium urinalysis results were fit as type M material. As discussed above, each chronic intake period was fit independently. Figures A-1 to A-4 show the fits to the 50th-percentile values for each intake period. The same intake periods were applied to the 84th-percentile values because the values followed a similar pattern. Table 5-2 summarizes the intake periods and corresponding intake rates for the 50th- and 84th-percentile values.

Table 5-2. Type M $^{239+240}$Pu intake periods and rates.

		Plutonium intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1946	12/31/1948	57.7	149.2	2.59
01/01/1949	12/31/1952	21.1	54.11	2.56
01/01/1953	12/31/1981	1.003	3.196	3.19
01/01/1982	12/31/1988	0.1336	1.132	8.47

Figure A-5 depicts the predicted excretion rates from all 50th-percentile type M intakes.

The large decrease in 50th-percentile bioassay results and intakes after 1981 resulted from a switch in reporting practices from a reporting level of 0.025 dpm to reporting all results. The MDA also decreased from 0.05 dpm to 0.02 dpm in 1984.

5.3.1.2 Type S

Because type S plutonium clears slowly from the body, the plutonium exposure was fit as a single chronic intake based on the bioassay measurements from 1982 to 1988. This period was used because the measurements were relatively consistent; in addition, because these are the most recent measurements, they had the lowest MDA and, therefore, were presumably the most accurate. See Section 6.1 for special instructions for using the type S intake.

Figure A-6 shows the predicted excretion rates for the 50th-percentile values based on a chronic intake for the entire set of years fitted to the bioassay data for the last 7 yr (1982 to 1988). The same intake period was applied to the 84th-percentile values because the values followed a similar pattern. Table 5-3 summarizes the intake period and corresponding intake rate for the 50th- and 84th-percentile values.

Table 5-3. Type S $^{239+240}$Pu intake period and rates.

		Plutonium intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1946	12/31/1988	0.5169	4.382	8.48

5.3.2 Uranium

Uranium at Hanford existed as mostly type F or S, but neither classification should be considered a perfect match to the uranium compounds, and type M cannot be ruled out. Therefore, all three types should be considered possible. Thorium exposure was associated with uranium exposure in 300 Area facilities from 1950 to 1970. Section 6.1.2 contains guidance for adding thorium to uranium intakes.

5.3.2.1 Type F

This section shows intakes when uranium urinalysis results were fit using a type F material. Figure A-7 shows the fit to the 50th-percentile values from all intakes. The figure depicts the expected excretion rate from an individual exposed for all the periods at the 50th-percentile intake rate. The same intake periods were applied to the 84th-percentile values because the values followed a similar pattern. Table 5-4 summarizes the intake periods and corresponding intake rates for the 50th- and 84th-percentile values.

Table 5-4. Type F uranium intake periods and rates.

		Uranium intake rate (µg/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1948	12/31/1952	17.42	58.35	3.35
01/01/1953	12/31/1956	12.3	39.45	3.21
01/01/1957	12/31/1961	17.73	61.65	3.48
01/01/1962	12/31/1974	10.61	31.09	2.93
01/01/1975	12/31/1983	1.281	7.037	5.49
01/01/1984	12/31/1988	0.4903	1.895	3.86

The decrease in intake rate in 1975 resulted from a decrease in the reporting level from 4 µg/L to 0.4 µg/L. That decrease may have also resulted in part from the shut downs of the PUREX and UO_3 plants from 1973 to 1983.

5.3.2.2 Type M

The intake periods used in the type F fits were applied to the type M material fits. Figure A-8 shows the fit to the 50th-percentile values from all intakes. The same intake periods were applied to the 84th-percentile values because the values followed a similar pattern. Table 5-5 summarizes the intake periods and corresponding intake rates for the 50th- and 84th-percentile values.

5.3.2.3 Type S

The intake periods used in the type F and M fits were applied to the type S material fits. As discussed, each chronic intake period for type S material was fit independently. Figures A-9 to A-14 show the individual fits for the 50th-percentile values. The 84th–percentile values were fit similarly. Table 5-6 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-5. Type M uranium intake periods and rates.

		Uranium intake rate (µg/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1948	12/31/1952	73.12	244.5	3.34
01/01/1953	12/31/1956	49.35	159	3.22
01/01/1957	12/31/1961	72.79	252.6	3.47
01/01/1962	12/31/1974	42.78	124.9	2.92
01/01/1975	12/31/1983	4.414	25.99	5.89
01/01/1984	12/31/1988	1.919	7.043	3.67

Table 5-6. Type S uranium intake periods and rates.

		Uranium intake rate (µg/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1948	12/31/1952	1,308	4,373	3.34
01/01/1953	12/31/1956	1,035	3,321	3.21
01/01/1957	12/31/1961	1,349	4,660	3.45
01/01/1962	12/31/1974	665.1	1,953	2.94
01/01/1975	12/31/1983	83.67	403.3	4.82
01/01/1984	12/31/1988	46.84	171.6	3.66

Figure A-15 shows the predicted excretion rates from all 50th-percentile value type S intakes.

5.3.3 Strontium-90

Only type F solubility was analyzed for ^{90}Sr. Figure A-16 shows the fit to the 50th-percentile values from all intakes. Table 5-7 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-7. Type F ^{90}Sr intake periods and rates.

		Sr-90 intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1965	12/31/1967	90.47	241.5	2.67
01/01/1968	12/31/1970	60.5	241.5	3.99
01/01/1971	12/31/1988	3.698	9.405	2.54

5.3.4 Promethium-147

5.3.4.1 Type M

Each chronic intake period for type M ^{147}Pm was fit independently. Figures A-17 and A-18 show the individual fits for the 50th-percentile values. The 84th-percentile values were fit similarly. Table 5-8 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-8. Type M ^{147}Pm intake periods and rates.

		^{147}Pm intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1966	12/31/1969	4,976	15,620	3.14
01/01/1970	12/31/1979	1,720	4,483	2.61

Figure A-19 shows the predicted excretion rates from all 50th-percentile value type M intakes.

5.3.4.2 Type S

Each chronic intake period for type S ^{147}Pm was fit independently. Figures A-20 and A-21 show the individual fits for the 50th-percentile values. The 84th–percentile values were fit similarly. Table 5-9 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-9. Type S ^{147}Pm intake periods and rates.

		Pm-147 intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1966	12/31/1969	131,500	411,400	3.13
01/01/1970	12/31/1979	34,810	90,850	2.61

Figure A-22 shows the predicted excretion rates from all 50th-percentile value type S intakes.

5.3.5 Zinc-65

Intakes of ^{65}Zn include a single acute intake in addition to the normal chronic intakes modeled. This acute intake was included to optimize the fit of the modeling results to the data. The data show a sudden increase in the last quarter of 1976 followed by a steady decrease over the next several quarters, which is indicative of an acute intake during the last quarter of 1976.

5.3.5.1 Inhalation Intakes

Absorption type S was used for ^{65}Zn inhalation intakes. Each chronic intake period for type S ^{65}Zn was fit independently. However, the acute intake on October 1, 1976, was modeled with the contemporaneous chronic intake. Figures A-23 to A-28 show the individual fits for the 50th-percentile values. The 84th-percentile values were fit similarly. Table 5-10 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-10. Type S zinc-65 inhalation intake periods and rates.

Start date	Stop date	Zinc-65 intake rate (dpm/d)		GSD
		50th-percentile	84th-percentile	
01/01/1960	12/31/1963	44.56	181.2	4.07
01/01/1964	12/31/1967	53.68	199.6	3.72
01/01/1968	12/31/1970	35.29	124.2	3.52
01/01/1971	12/31/1972	29.88	94.31	3.16
01/01/1973	12/31/1977	12.58	42.59	3.39
01/01/1978	12/31/1984	7.411	21.83	2.95
10/01/1976[a]	-	2555[b]	14260[b]	5.58

a. This is the date of the acute intake.
b. This intake has units of dpm for an acute intake rather than dpm/d.

Figure A-29 shows the predicted excretion rates from all 50th-percentile value type S intakes.

The once-through-cooled reactors were being shutdown from 1964 to 1971.

5.3.5.2 Ingestion Intakes

The ingestion intakes of ^{65}Zn were modeled together. Figure A-30 shows the fit to the 50th-percentile values from all intakes. The 84th–percentile values were fit similarly. Table 5-11 summarizes the intake rates for the 50th- and 84th-percentile values. Ingestion intakes after the once-through-cooled reactors were shut down (after 1972) were not considered plausible.

Table 5-11. Zinc-65 ingestion intake periods and rates.

Start date	Stop date	Zn-65 intake rate (dpm/d)		GSD
		50th-percentile	84th-percentile	
01/01/1960	12/31/1963	26.21	105.0	4.01
01/01/1964	12/31/1967	27.64	103.4	3.74
01/01/1968	12/31/1970	16.69	57.34	3.44
01/01/1971	12/31/1972	13.06	39.86	3.05

5.3.6 Sodium-24

5.3.6.1 Inhalation Intakes

Absorption type F was used for ^{24}Na inhalation intakes. Figure A-31 shows the fit to the 50th-percentile values from all intakes. The 84th–percentile values were fit similarly. Table 5-12 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-12. Type F ^{24}Na inhalation intake periods and rates.

		Na-24 intake rate (pCi/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1960	09/30/1963	310.3	942.6	3.04
10/01/1963	12/31/1963	1921	6939	3.61
01/01/1964	09/30/1964	452.7	1410	3.11
10/01/1964	03/31/1965	1037.6	3654	3.52
04/01/1965	12/31/1973	452.7	1410	3.11
01/01/1974	12/31/1984	250.8	680.7	2.71

5.3.6.2 Ingestion Intakes

The ingestion intakes of ^{24}Na were modeled together. Figure A-32 shows the fit to the 50th-percentile values from all intakes. These depict the expected excretion rates from an individual exposed for all the periods at the 50th- and 84th-percentile intake rates. Table 5-13 summarizes the intake rates for the 50th- and 84th-percentile values. Ingestion intakes after the once-through-cooled reactors were shut down (by 1971 because of the very short half-life of ^{24}Na) were not considered plausible.

Table 5-13. Sodium-24 ingestion intake periods and rates.

		Na-24 intake rate (pCi/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1960	09/30/1963	205.6	624.7	3.04
10/01/1963	12/31/1963	1274	4599	3.61
01/01/1964	09/30/1964	311.9	986.3	3.16
10/01/1964	03/31/1965	687.6	2421	3.52
04/01/1965	12/31/1971	311.9	986.3	3.16

5.3.7 Cesium-137

Only absorption type F was analyzed for ^{137}Cs. Figure A-33 shows the fit to the 50th-percentile values from all intakes. Table 5-14 summarizes the intake rates for the 50th- and 84th-percentile values.

Table 5-14. Type F ^{137}Cs intake periods and rates.

		Cs-137 intake rate (dpm/d)		
Start date	Stop date	50th-percentile	84th-percentile	GSD
01/01/1960	12/31/1960	118.6	173.7	1.46
01/01/1961	12/31/1961	39.08	61.74	1.58
01/01/1962	12/31/1962	55.23	81.79	1.48
01/01/1963	12/31/1964	246.8	374.8	1.52
01/01/1965	12/31/1966	132.6	213.9	1.61
01/01/1967	12/31/1967	44.34	85.13	1.92
01/01/1968	12/31/1976	28.38	58.36	2.06
01/01/1977	12/31/1988	10.13	26.08	2.57

6.0 ASSIGNMENT OF INTAKES AND DOSES

Tables 6-1 to 6-3 and 6-6 to 6-10 summarize the 50th-percentile intake rates and GSDs for each primary radionuclide over their respective periods and solubility classes. Table 6-4 lists the potential intake rates and GSDs for thorium. When calculating doses to individuals from bioassay data, a GSD of 3 has been used to account for biological variation and uncertainty in the models. It was considered inappropriate to assign a value less than 3 for the coworker data. Therefore, a GSD of at least 3 was assigned for each of the intake periods. The GSDs for different intake periods have also been conservatively adjusted for consistency between intake periods for calculational efficiency.

Bioassay results used to establish coworker intakes did not cover all the years of possible exposure at Hanford. Extrapolation from monitored years to unmonitored years is discussed as part of the overall discussion of intakes for each radionuclide. The history of production at Hanford is relevant to those discussions. Figure 1 shows how a figure of merit for production (tons of uranium processed in the reactors times the burnup) varied from 1944 to 1972. This unit is especially relevant for the production of fission products and to a reasonable extent for production of activation products. The figure shows that the period of highest production at Hanford was from about 1958 to 1968, which overlaps with the period of whole-body counting and ^{90}Sr urinalysis.

6.1 PLUTONIUM

Tables 6-1 and 6-2 list the plutonium intakes and associated GSDs for each period for types M and S solubility classes, respectively. A small amount of plutonium was produced in 1944 (T Plant started operations in December 1944), and more was produced in 1945. A tolerance air concentration level was implemented at least by October 1945, which was reduced by a factor of 25 sometime between 1945 and 1948 (Cantril 1945; Parker 1947). Because production from 1946 to 1948 was comparable to that in 1945, and allowing for the higher tolerance air concentration, an intake at 25 times the rate for 1946 to 1948 should be assigned to the period from December 1944 to December 1945. Type S plutonium would not have been likely during those first 12 months of operation.

Because of the interdependence between the bioassay results, it is not possible to fit type S plutonium to the data in a manner that would be representative of all individuals for all time periods. Therefore, only a minimizing intake has been calculated for type S plutonium. Type M plutonium should be applied for all systemic organs. For ***non-systemic*** **(respiratory and GI tracts) organs**, the following shall be done:

1. Run the type M intakes. If this does not result in a draft PoC >50% [final PoC is determined by the Department of Labor],

2. Run the minimizing type S intake. If this still does not yield a draft PoC >50%,

3. Manually fit the coworker bioassay data for the time frame of interest for the employee, using the assumption of type S material. Standard fitting techniques should be used; acute or chronic intakes can be assigned, depending on the patterns in the data. Both the 50th - and 84th - percentile data must be fit using the same intake dates or periods; the 50th-percentile intakes are used to assign the intake and the 84th-percentile is used to determine the GSD for each intake. For input into IREP, note that lognormal distributions with different GSDs cannot be summed in a single IREP line.

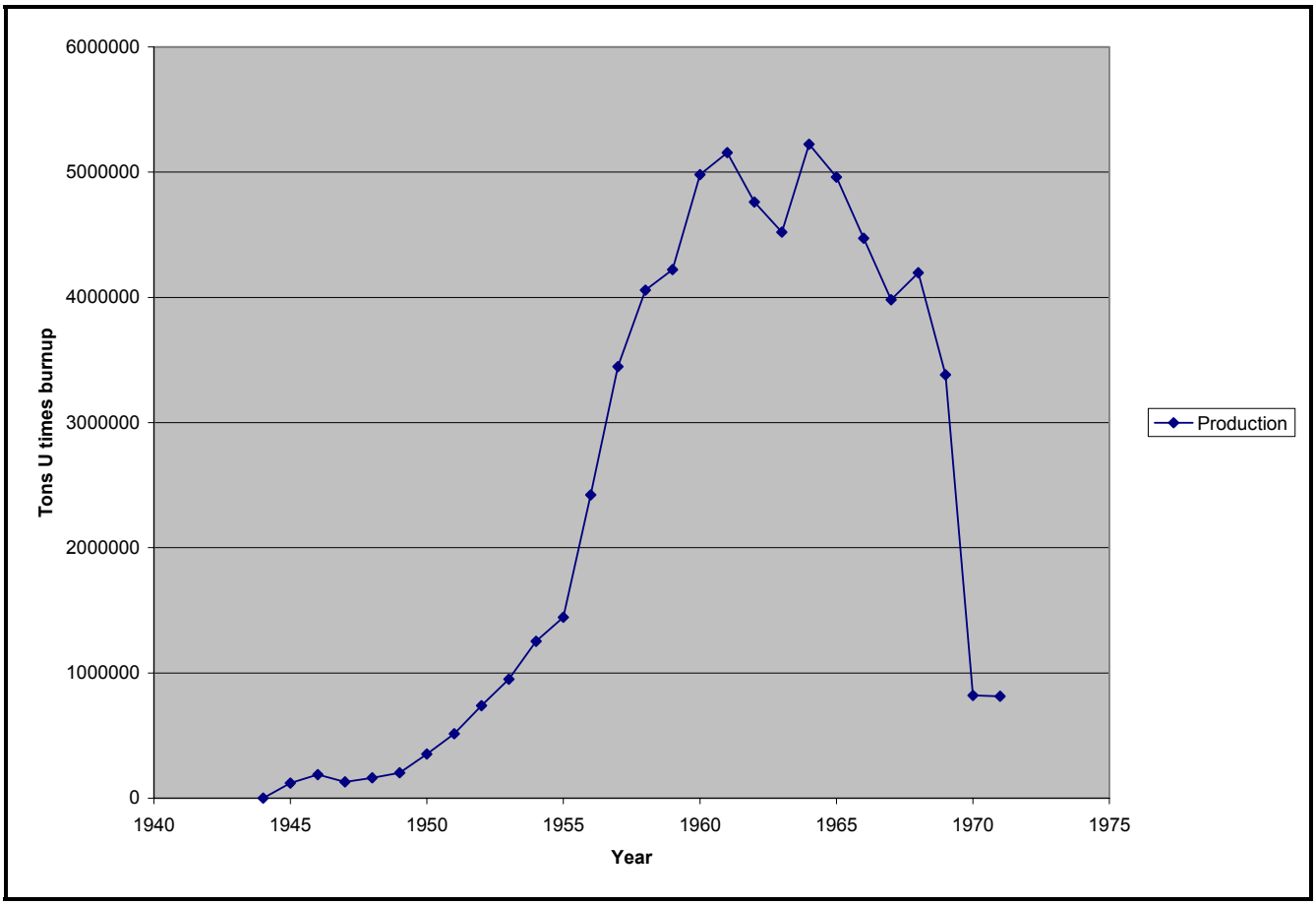

Figure 1. Production rates in tons of uranium times fuel burnup, 1944 to 1972.

Table 6-1. Type M plutonium intake periods and rates.

Start date	Stop date	Plutonium intake rate (dpm/d)	
		50th-percentile	GSD
12/01/1944	12/31/1945	1,440[a]	3.00
01/01/1946	12/31/1948	57.7	3.00
01/01/1949	12/31/1952	21.1	3.00
01/01/1953	12/31/1981	1.003	3.19
01/01/1982	12/31/1988	0.1336	8.47

a. Assumed to be 25 times the 1946-48 rate.

Table 6-2. Type S plutonium intake period and rates.

Start date	Stop date	Plutonium intake rate (dpm/d)	
		50th-percentile	GSD
01/01/1946	12/31/1988	0.5169	8.48

4. The more claimant-favorable doses from the type M and S fits should be assigned.

6.2 URANIUM AND THORIUM

Table 6-3 lists the uranium intakes and associated GSDs for each period. The values were adjusted from micrograms per day to picocuries per day for input into IMBA. Uranium bioassay started in 1947, but the early results were not considered reliable. Exposure to uranium in the 300 Area started in March 1944. The tolerance air concentration in 1945 was three times higher than the required

respiratory protection level implemented sometime between 1945 and 1947 (Cantril 1945; Parker 1947). Because production quantities were similar or smaller from 1944 to 1947 than for 1948 and later the tolerance concentration was three times greater, intakes for 1944 to 1947 were assumed to be 3 times higher than for 1948 to 1952.

Table 6-3. Uranium intake periods and rates.

		Uranium intake, pCi/d					
		Type F		Type M		Type S	
Start date	Stop date	Intake	GSD	Intake	GSD	Intake	GSD
03/01/1944	12/31/1947[a]	36.87	3.48	154.7	3.47	2,768	3.45
01/01/1948	12/31/1951	12.29	3.48	51.58	3.47	922.7	3.45
01/01/1952	12/31/1952	15.85	3.48	66.53	3.47	1,190	3.45
01/01/1953	12/31/1956	11.19	3.48	44.90	3.47	941.7	3.45
01/01/1957	12/31/1961	16.13	3.00	66.23	3.00	1,227	3.00
01/01/1962	12/31/1974	9.654	5.49	38.93	5.89	605.2	4.82
01/01/1975	12/31/1983	1.166	3.86	4.016	3.67	76.13	3.66
01/01/1984	12/31/1988	0.446	3.86	1.746	3.67	42.62	3.66

a. Intakes in this period assumed to be 3 times the 1948-51 intakes.

If the energy employee worked in the 300 Area and was associated with uranium in any way, then exposure to thorium cannot be ruled out. Exposure could have occurred as early as 1950. The same would apply to workers at the PUREX Plant from 1966 to 1971. Although there was less thorium than uranium by mass handled at Hanford, the potential for intake could have been similar on an individual worker basis. Therefore, the same intake rates were assumed. Table 6-4 shows thorium intake periods and rates. The degree of equilibrium between ^{232}Th and decay products including ^{228}Th is not known. Similar processes at Y-12 caused separation between thorium and the radium and lead decay products resulting in disequilibrium between ^{232}Th and ^{228}Th with the activity ratio 228/232 remaining around 0.6 for about 4 to 10 years after purification. A ratio generally-applicable over most years is 0.8, which is being used for the Y-12 thorium exposures, and hence, is recommended for this application also.

Table 6-4. Thorium intake periods and rates.

			Thorium intake, pCi/d			
			Type M		Type S	
Exposure area	Start date	Stop date	Intake	GSD	Intake	GSD
300 Area, uranium facilities	01/01/1950	12/31/1951	51.58	3.47	922.7	3.45
	01/01/1952	12/31/1952	66.53	3.47	1,190	3.45
	01/01/1953	12/31/1956	44.90	3.47	941.7	3.45
	01/01/1957	12/31/1961	66.23	3.00	1,227	3.00
	01/01/1962	12/31/1970	38.93	5.89	605.2	4.82
PUREX	01/01/1966	12/31/1971	66.23	3.00	1,227	3.00

Starting in 1952, uranium at Hanford was recycled uranium with contaminants. Table 6-5 shows the activities of contaminants to apply to the uranium intakes in Table 6-26 from 1952 to 1988.

Table 6-5. Contaminants in recycled uranium (units are pCi contaminant per pCi U).

Pu-239	Np-237	Th-232	Tc-99	Ru-106	Zr-95	Nb-95
4.4 E-4	4.4 E-4	5.5 E-6	2.2E-1	4.4 E-2	1.1 E-2	1.1 E-2

6.3 STRONTIUM-90

Table 6-6 lists the ^{90}Sr intakes and associated GSDs for each period. Production of fission products in general from 1965 to 1967 was as great as any time in the history of Hanford, and build-up of ^{90}Sr as a contamination source had occurred over 20 yr of operation. Air concentration limits were essentially unchanged from 1947 to the present (Parker 1947; Patterson 1949). The tolerance air concentration in 1945 was 10 times the 1947 value. Therefore, it is reasonable to apply the ^{90}Sr intake rates from the 1965 to 1967 period to the 1947 to 1964 period and to apply 10 times those rates to the 1944 to 1946 period.

Table 6-6. Type F ^{90}Sr intake periods and rates.

		Sr-90 intake rate (dpm/d)	
Start date	Stop date	Intake	GSD
12/01/1944	12/31/1946	904.7[a]	3.00
01/01/1947	12/31/1964	90.47[b]	3.00
01/01/1965	12/31/1967	90.47	3.00
01/01/1968	12/31/1970	60.5	3.99
01/01/1971	12/31/1988	3.698	3.00

a. Intake rate assumed to be 10 times the rate for 1965 to 1967.
b. Intake rate assumed to be the same as the rate for 1965 to 1967.

6.4 PROMETHIUM-147

Table 6-7 lists the ^{147}Pm intakes and associated GSDs for each period. Promethium-147 intakes should be applied only to workers who were in the 325 or 308 Buildings from 1966 to 1979.

Table 6-7. Promethium-147 intake periods and rates.

		Pm-147 intake (dpm/d)			
		Type M		Type S	
Start date	Stop date	Intake	GSD	Intake	GSD
01/01/1966	12/31/1969	4,976	3.14	131,500	3.13
01/01/1970	12/31/1979	1,720	3.00	34,810	3.00

6.5 ZINC-65

Table 6-8 lists the zinc intakes and associated GSDs for each period. Similar to ^{90}Sr, the intake rates before 1960 were assumed based on smaller production and similar air concentration limits, with the exception of the 1944 to 1946 period. Because the intakes are based on whole-body counting, which measures activity in the body from all intake pathways, the dose reconstructor should apply the more claimant-favorable of the inhalation or ingestion intake but not both in the same year. If ingestion is used and the exposure period continues to 1973 or more recent, then the intake mode will have to be switched from ingestion to inhalation for the latter years. Since ingestion was determined to not be plausible after 1972, the intakes for inhalation must be assumed after this date, even when ingestion has been assumed prior to this date.

6.6 SODIUM-24

Table 6-9 lists the ^{24}Na intakes and associated GSDs for each period. As a claimant-favorable assumption, the highest intake rate within a given year was used to set the intake rate for the entire year. Similar to ^{90}Sr, the intake rates before 1960 were assumed based on smaller production and similar air concentration limits with the exception of the 1944 to 1946 period. Because the intakes were based on whole-body counting, which measures activity in the body from all intake pathways,

Table 6-8. Zinc-65 intake periods and rates.

		Zn-65 intake (pCi/d)			
		Inhalation		Ingestion	
Start date	Stop date	Intake	GSD	Intake	GSD
12/01/1944	12/31/1946[a]	445.6	4.07	262	4.01
01/01/1947	12/31/1959[b]	44.56	4.07	26.2	4.01
01/01/1960	12/31/1963	44.56	4.07	26.2	4.01
01/01/1964	12/31/1967	53.68	4.07	27.64	4.01
01/01/1968	12/31/1970	35.29	3.52	16.69	3.44
01/01/1971	12/31/1972	29.88	3.52	13.06	3.05
01/01/1973	12/31/1977	12.58	3.52	NA[c]	
01/01/1978	12/31/1984	7.411	3.00	NA	
10/1/1976[d]	-	2555[e]	5.58	NA	

a. Intake rates assumed to be 10 times the rates for 1960 to 1963.
b. Intake rates assumed to be the same as the rates for 1960 to 1963.
c. NA = not applicable.
d. This is the date of the acute intake.
e. This intake has units of dpm for an acute intake rather than dpm/d.

the dose reconstructor should apply the more claimant-favorable of the inhalation or ingestion intakes, but not both in the same year. If ingestion is used and the exposure period continues to 1972 or later, then the intake mode will have to be switched from ingestion to inhalation for the latter years, that is, the intakes for inhalation must be assumed after 1971, even when ingestion has been assumed prior to this date.

Table 6-9. Sodium-24 intake periods and rates.

		Na-24 intake (pCi/d)			
		Inhalation Type F		Ingestion	
Start date	Stop date	Intake	GSD	Intake	GSD
12/1/1944	12/31/1946[a]	3,103	3.04	2,056	3.04
01/01/1947	12/31/1959[b]	310.3	3.04	205.6	3.04
01/01/1960	12/31/1962	310.3	3.04	205.6	3.04
01/01/1963	12/31/1963	1,921	3.61	1,274	3.61
01/01/1964	12/31/1965	1,038	3.72	687.6	3.61
01/01/1966	12/31/1971	452.7	3.11	300	3.61
01/01/1972	12/31/1973	452.7	3.11	NA[c]	NA
01/01/1974	12/31/1984	250.8	3.11	NA	NA

a. Intake rates assumed to be 10 times the rates for 1960 to 1962.
b. Intake rates assumed to be the same as the rates for 1960 to 1962.
c. NA = not applicable.

6.7 CESIUM-137

Table 6-10 lists the ^{137}Cs intakes and associated GSDs for each period. Similar to ^{90}Sr, the intake rates before 1960 were assumed based on smaller production and similar air concentration limits, with the exception of the period from 1944 to 1946.

6.8 ADDITIONAL RADIONUCLIDES

A large number of different radionuclides were present at Hanford at various times, but the available bioassay data for radionuclides in addition to those considered in this report were considered to be too few to be statistically reliable for intake estimation. Workers exposed to ^{137}Cs, ^{90}Sr, ^{24}Na, and ^{65}Zn

Table 6-10. Type F cesium-137 intake periods and rates.

		Cs-137 intake rate (dpm/d)	
Start date	**Stop date**	**Intake**	**GSD**
12/1/1944	12/31/1946	1,186[a]	3.00
01/01/1947	12/31/1959	118.6[b]	3.00
01/01/1960	12/31/1960	118.6	3.00
01/01/1961	12/31/1961	39.08	3.00
01/01/1962	12/31/1962	55.23	3.00
01/01/1963	12/31/1964	246.8	3.00
01/01/1965	12/31/1966	132.6	3.00
01/01/1967	12/31/1967	44.34	3.00
01/01/1968	12/31/1976	28.38	3.00
01/01/1977	12/31/1988	10.13	3.00

a. Intake rate assumed to be 10 times the rate for 1960.
b. Intake rate assumed to be the same as the rate for 1960.

could also have been exposed to other fission and activation products. From 1960 to 1988, intakes of most fission or activation products would have been detectable in whole-body counts. However, the recording practice for fission and activation products other than ^{137}Cs, ^{24}Na, and ^{65}Zn was not amenable to statistical analysis. Measured body burdens less than 1% of the MPBBs were often simply listed as a trace. For ^{51}Cr, ^{60}Co, ^{106}Ru, and ^{144}Ce, for instance, 1% of the MPBBs are 8,000, 100, 30, and 50 nCi, respectively. It is clear from the database that body burdens less than these values were often reported, but it is not known with certainty how to interpret a whole-body count that lists, for example, ^{60}Co but has a blank result field. Therefore, other methods were investigated for the assignment of intakes of unmeasured or unquantified fission and activation products.

Use of the ratios of fission products in irradiated fuel was one evaluated approach. Limitations to this approach include:

- Excludes activation products.
- Dependent on assumed cooling time before fuel is dissolved.
- Ignores how radionuclides in fuel become contamination. Ratios of contamination would be different at the various facilities; for instance, reactors versus reactor fuel storage pools versus separations plants versus waste management facilities. In accessible contaminated areas, ratios of long-lived radionuclides would have increased over time relative to short-lived radionuclides due to chronic build-up.

Another investigated approach was to assign intakes based on ratios in airborne effluents. Limitations to this approach include:

- Data were available for effluents from the separations plants only, and these were not representative of the contamination ratios at the reactors or waste management facilities.
- Activation products were underrepresented.
- This method favors volatile radionuclides, whereas workers were more likely exposed to the less volatile radionuclides (i.e., the ones that were not vented through the stack).
- The removal efficiencies of the effluent clean-up systems might not have been the same for all radionuclides (which is clearly true for radioiodines, but could also be true for particulates).

The two methods did not produce consistent results. For instance, Table 6-11 shows the range and average ratios in airborne effluents from Hanford's separations plants for the 1945 to 1971 period for several principal radionuclides versus the range in the fuel for discharge versus 3 yr of cooling. In general, the average ratios in the effluents were equal to or greater than the ratios in the fuel at discharge. One might expect the average in the effluents to fall between the ratio in the fuel at discharge versus after three years of cooling.

Table 6-11. Comparison of radionuclide ratios in airborne effluents.

	Range in effluents, 1945-71[a]	Average in effluents, 1944-71[a]	In N-reactor fuel at discharge[b]	In N-reactor fuel, 3-yr cooling time[b]
Ce-144/Cs-137	8.40-270	110	29	2.1
Ru-106/Cs-137	2.90-830	59	8.7	0.62
Nb+Zr-95/Cs-137	1.10-200	23	164	0.0024
Ce-144/Sr-90	7.40- 58	33	33	2.4
Ru-106/Sr-90	1.00-720	50	5.6	0.72
Zr+Nb-95/Sr-90	0.28- 61	19	120	0.0028

a. Based on data in (Heeb 1994) for airborne effluents from Hanford's separations plants.
b. Based on ORIGEN 2 computer calculations for N-Reactor MKIV 6% fuel.

Because a method of determining ratios of other fission and activation products to ^{137}Cs or ^{90}Sr was not considered reliable, the approach in the Hanford internal dosimetry technical basis document (ORAUT 2004) for unmonitored workers was adapted to cover the unmonitored fission and activation products. Table 5.7-1 in ORAUT (2004) establishes intakes for workers with external monitoring but no bioassay based on limiting air concentrations or air concentrations for which respiratory protection was required. Table 6-12 lists the parts of that table applicable to fission and activation products not covered by coworker bioassay measurements. Which particulate fission or activation radionuclide the intakes apply to depends on the organ of concern. Table 6-13 lists the radionuclide and absorption type that produce the highest dose to the organs listed (from Table 5.7-2 in ORAUT 2004).

It is unlikely that an unmonitored worker had chronic intakes of a large number of radionuclides in any 1 yr. Intakes of plutonium, uranium ^{90}Sr, ^{65}Zn, ^{24}Na, and ^{137}Cs should be assigned to all workers; intakes of thorium should be assigned per Table 6-5; and ^{147}Pm should be added for workers involved in the ^{147}Pm heat source program. One additional (remainder) radionuclide should be added to the list to cover the unmonitored fission or activation products in accordance with the guidance in Tables 6-12 and 6-13. The distribution for the remainder radionuclide should be triangular with a minimum of zero, the mode from Table 6-12, and a maximum of twice the mode.

Table 6-12. Intakes for fission or activation products other than ^{90}Sr, ^{65}Zn, ^{24}Na, or ^{137}Cs.

Period	Radioactive material	Limiting air concentration ($\mu Ci/cm^3$)	Daily intake (dpm/d)
1944-47[a]	Particulate fission/activation products other than Sr-90, Cs-137, Zn-65, Na-24	1×10^{-8}	14,700[b]
	I-131 vapor[c,d]	NA[e]	166,000
1948-52[a]	Particulate fission/activation products other than Sr-90, Cs-137, Zn-65, Na-24	1×10^{-9}	733[b]
	I-131 vapor[c,d]	NA	166,000
1953-67	Particulate fission/activation products other than Sr-90, Cs-137, Zn-65, Na-24	3×10^{-10}	22.2[b]
	I-131 vapor[c]	9×10^{-9}	1,310
1968-88	Particulate fission/activation products other than Sr-90, Cs-137, Zn-65, Na-24	1×10^{-9}	73.3[b]
	I-131 vapor[c]	9×10^{-9}	1,310

a. Based on air concentrations that required respiratory protection.
b. One-half of values in ORAUT (2004) to account for ^{90}Sr, ^{137}Cs, ^{65}Zn, and ^{24}Na.
c. Reactor or separations plant workers only.
d. Based on tolerance thyroid burden.
e. NA = not applicable.

Table 6-13. Fission or activation radionuclide chooser for unmonitored workers.

Organ of concern	Beta/gamma radionuclide and absorption type	
	Operating reactors	Fuel separation plants, waste management facilities
Adrenals	Co-60 S[a]	Ru-106 F
Bone surface	Zr-95 F[a]	Zr-95 F
Brain	Ru-106 F	Ru-106 F
Breast	Ru-106 F	Ru-106 F
Colon	Ru-106 S	Ru-106 S
Esophagus	Ru-106 F	Ru-106 F
Extra thoracic	Co-60 S	Ru-106 S
Gall bladder	Ru-106 F[a]	Ru-106 F
Heart	Co-60 S	Ru-106 F
Kidneys	Ru-106 F[a]	Ru-106 F
Liver	Ce-144 M[a]	Ce-144 M
Lower large intestine	Ru-106 S[a]	Ru-106 S
Lung	Ru-106 S	Ru-106 S
Muscle	Ru-106 F	Ru-106 F
Ovaries	Ru-106 F	Ru-106 F
Pancreas	Ru-106 F	Ru-106 F
Red bone marrow	Ce-144 M[a]	Ce-144 M
Small intestine	Ru-106 F[a]	Ru-106 F
Skin	Ru-106 F	Ru-106 F
Spleen	Ru-106 F	Ru-106 F
Stomach	Ru-106 F[a]	Ru-106 F
Testes	Ru-106 F	Ru-106 F
Thymus	Co-60 S	Ru-106 F
Thyroid	Ru-106 F	Ru-106 F
Upper large intestine	Ru-106 F	Ru-106 F
Urinary bladder	Ru-106 F	Ru-106 F
Uterus	Ru-106 F	Ru-106 F

a. Substitute Eu-154 M if individual worked at N Reactor.

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Table A-1. Statistical summary of ^{239}Pu 24-hr urinary excretion rates, 1946-1988.[a]

Effective bioassay date	GM[b] (50th) dpm/d	GM*GSD[c] (84th) dpm/d
07/01/1946	0.25402	0.66092
07/01/1947	0.20476	0.50991
04/01/1948	0.21047	0.53721
10/1/1948	0.22645	0.60437
07/01/1949	0.10752	0.28933
07/01/1950	0.10249	0.25412
07/01/1951	0.10358	0.26263
07/01/1952	0.05707	0.14968
04/01/1953	0.01647	0.04436
10/1/1953	0.01724	0.04873
02/15/1954	0.01704	0.04637
05/15/1954	0.01746	0.04932
08/15/1954	0.01765	0.05080
11/15/1954	0.01697	0.04609
02/15/1955	0.01671	0.04478
05/15/1955	0.01695	0.04624
08/15/1955	0.01746	0.05021
11/15/1955	0.01681	0.04538
02/15/1956	0.01703	0.04723
05/15/1956	0.01716	0.04803
08/15/1956	0.01724	0.04828
11/15/1956	0.01756	0.04956
02/15/1957	0.01659	0.04369
05/15/1957	0.01699	0.04599
08/15/1957	0.01663	0.04360
11/15/1957	0.01712	0.04671
02/15/1958	0.01576	0.06661
05/15/1958	0.01089	0.03745
08/15/1958	0.01001	0.03106
11/15/1958	0.01240	0.05037
02/15/1959	0.01265	0.05288
05/15/1959	0.01163	0.04018
08/15/1959	0.01058	0.03276
11/15/1959	0.01098	0.03388
02/15/1960	0.01237	0.04317
05/15/1960	0.01002	0.02983
08/15/1960	0.00980	0.02880
11/15/1960	0.00980	0.02931
02/15/1961	0.00977	0.02866
05/15/1961	0.00984	0.02971
08/15/1961	0.01022	0.03099
11/15/1961	0.00990	0.02813
02/15/1962	0.00948	0.02621
05/15/1962	0.01091	0.03307
08/15/1962	0.01235	0.04221
11/15/1962	0.01061	0.03407
02/15/1963	0.01100	0.03651
05/15/1963	0.01276	0.04553
08/15/1963	0.01166	0.03917
11/15/1963	0.01479	0.05371
02/15/1964	0.01826	0.06779
05/15/1964	0.02133	0.08054
08/15/1964	0.02435	0.08191
11/15/1964	0.02067	0.07232
02/15/1965	0.01409	0.04706
05/15/1965	0.01380	0.04542
08/15/1965	0.01248	0.03685
11/15/1965	0.01556	0.04811
02/15/1966	0.01197	0.03675
05/15/1966	0.01152	0.03613
08/15/1966	0.01354	0.04801
11/15/1966	0.01200	0.04220
02/15/1967	0.01330	0.05292
05/15/1967	0.02204	0.11370
08/15/1967	0.01175	0.04248
11/15/1967	0.01338	0.05001
02/15/1968	0.01216	0.04585
05/15/1968	0.01078	0.03891
08/15/1968	0.01397	0.06615
11/15/1968	0.01192	0.04489
02/15/1969	0.01321	0.04680
05/15/1969	0.00952	0.02753
08/15/1969	0.01101	0.03788
11/15/1969	0.01095	0.03868
02/15/1970	0.00974	0.03019
05/15/1970	0.0888	0.02567
08/15/1970	0.00980	0.03067
11/15/1970	0.01307	0.05338
02/15/1971	0.00933	0.02895
05/15/1971	0.00993	0.03206
08/15/1971	0.01126	0.03955
11/15/1971	0.01089	0.03976
02/15/1972	0.01179	0.04290
05/15/1972	0.01013	0.03254
08/15/1972	0.00973	0.03035
11/15/1972	0.01073	0.03642
02/15/1973	0.01107	0.03977
05/15/1973	0.00948	0.02877
08/15/1973	0.00945	0.02812
11/15/1973	0.00875	0.02403
02/15/1974	0.00885	0.02454
05/15/1974	0.00900	0.02532
08/15/1974	0.00911	0.02602
11/15/1974	0.01119	0.03852
02/15/1975	0.00910	0.02516
05/15/1975	0.00953	0.02738
08/15/1975	0.00802	0.02030
11/15/1975	0.00838	0.02233
02/15/1976	0.00857	0.02433
05/15/1976	0.00835	0.02245
08/15/1976	0.00801	0.02006
11/15/1976	0.00898	0.02764
02/15/1977	0.00871	0.02336
05/15/1977	0.00875	0.02371
08/15/1977	0.00835	0.02161
11/15/1977	0.00812	0.02061
02/15/1978	0.00878	0.02468
05/15/1978	0.00906	0.02664
08/15/1978	0.00836	0.02192
11/15/1978	0.00825	0.02180
02/15/1979	0.00871	0.02373
05/15/1979	0.00849	0.02278
08/15/1979	0.00851	0.02273
11/15/1979	0.00818	0.02095
02/15/1980	0.00821	0.02140
05/15/1980	0.00865	0.02388
08/15/1980	0.00870	0.02426
11/15/1980	0.00900	0.02488
02/15/1981	0.00799	0.02036
05/15/1981	0.00827	0.02204
8/5/1981	0.00851	0.02341
11/5/1981	0.00109	0.00644
02/15/1982	0.00069	0.00973
05/15/1982	0.00053	0.00572
08/15/1982	0.00083	0.00647
11/15/1982	0.00149	0.01120
02/15/1983	0.00113	0.00661
05/15/1983	0.00087	0.00497
08/15/1983	0.00094	0.00738
11/15/1983	0.00083	0.00589
02/15/1984	0.00132	0.00760
05/15/1984	0.00062	0.01534
08/15/1984	0.00090	0.00810
11/15/1984	0.00099	0.00860
02/15/1985	0.00116	0.01028
05/15/1985	0.00056	0.00531
08/15/1985	0.00076	0.00541
11/15/1985	0.00073	0.00389
02/15/1986	0.00065	0.00635
05/15/1986	0.00069	0.01717
08/15/1986	0.00099	0.00725
11/15/1986	0.00050	0.00463
02/15/1987	0.00069	0.00551
05/15/1987	0.00065	0.00471
08/15/1987	0.00086	0.00488
11/15/1987	0.00048	0.00411
02/15/1988	0.00080	0.00395
05/15/1988	0.00052	0.00312
08/15/1988	0.00064	0.00339
11/15/1988	0.00020	0.00203

a. For 1946 through 1949, the Pu-239 values were calculated as 0.824 of the total Pu alpha values; for 1950 through 1954, the Pu-239 values were calculated as 0.830 of the total Pu alpha values, for 1951 through 08/15/1983, the Pu-239 values were calculated as 0.835 of the total Pu alpha values.
b. GM = geometric mean or 50th-percentile value of the fitted line.
c. GSD = geometric standard deviation; GM*GSD is the 84th-percentile value of the fitted line.

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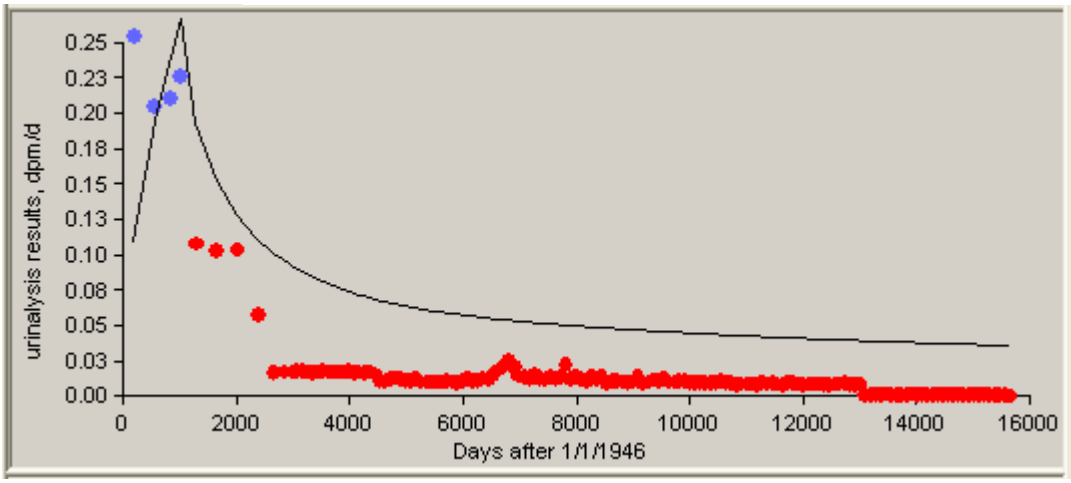

Figure A-1. 50th-percentile plutonium urinalysis data for intakes of Type M material, 1946 to 1948.

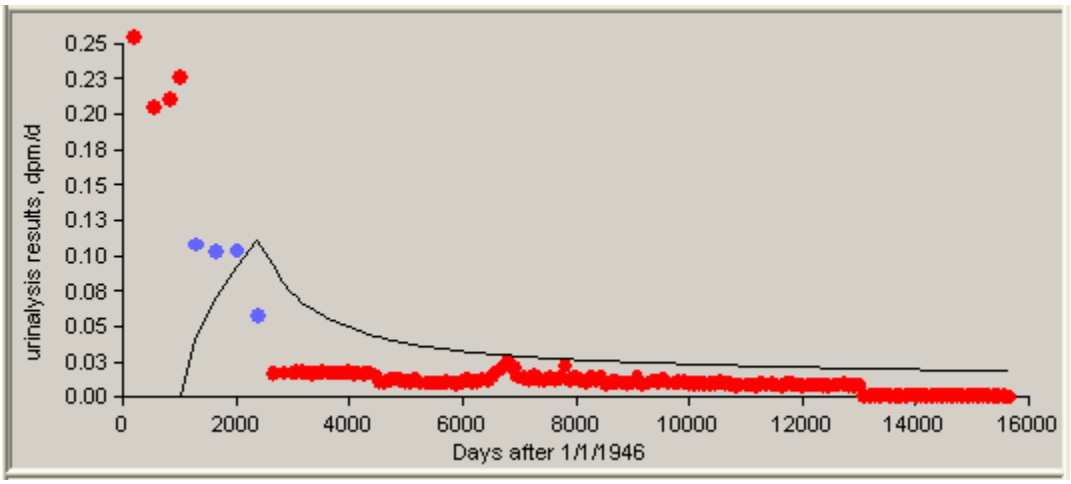

Figure A-2. 50th-percentile plutonium urinalysis data for intakes of Type M material, 1949 to 1952.

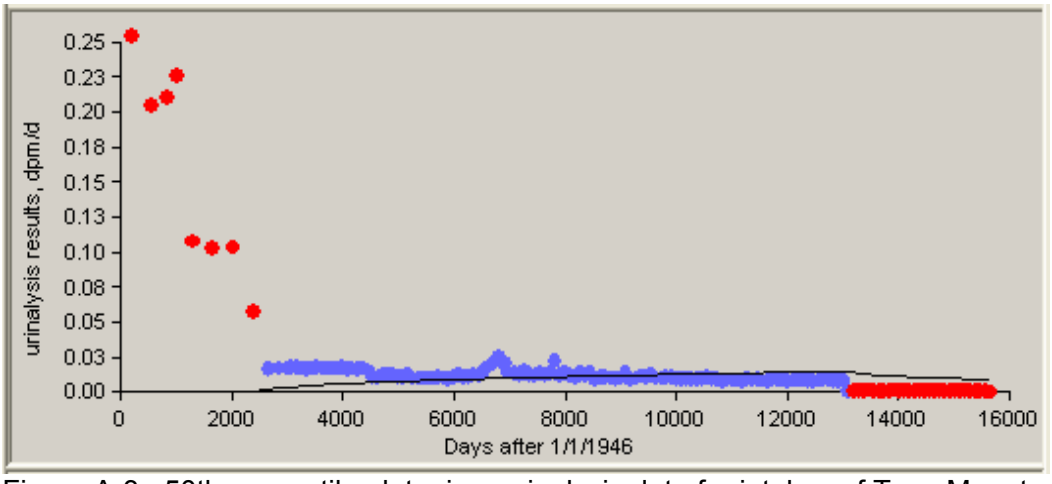

Figure A-3. 50th-percentile plutonium urinalysis data for intakes of Type M material, 1953 to 1981.

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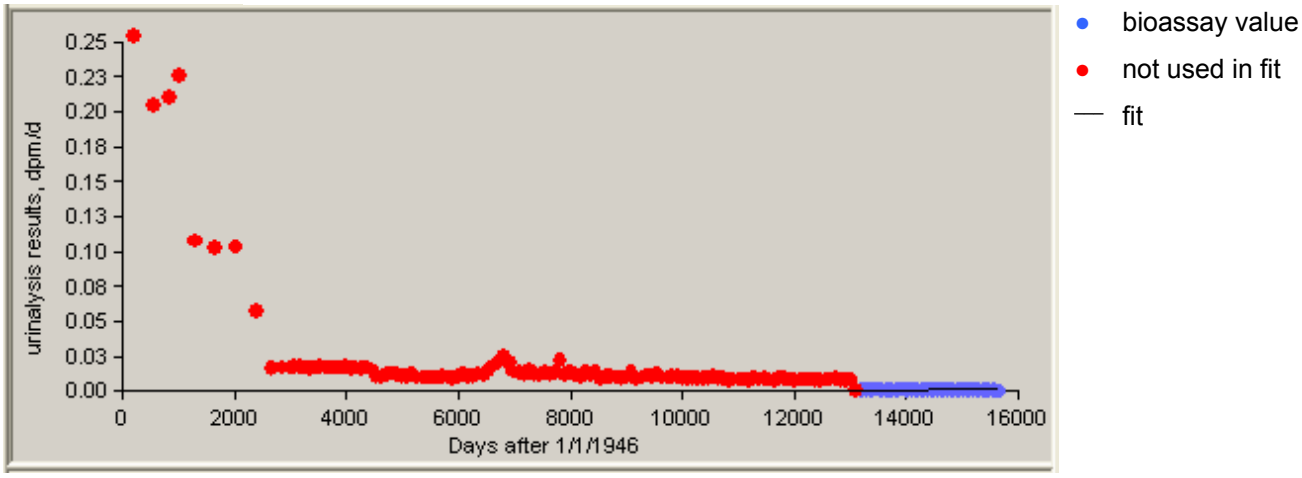

Figure A-4. 50th-percentile plutonium urinalysis data for intakes of Type M material, 1982 to 1988.

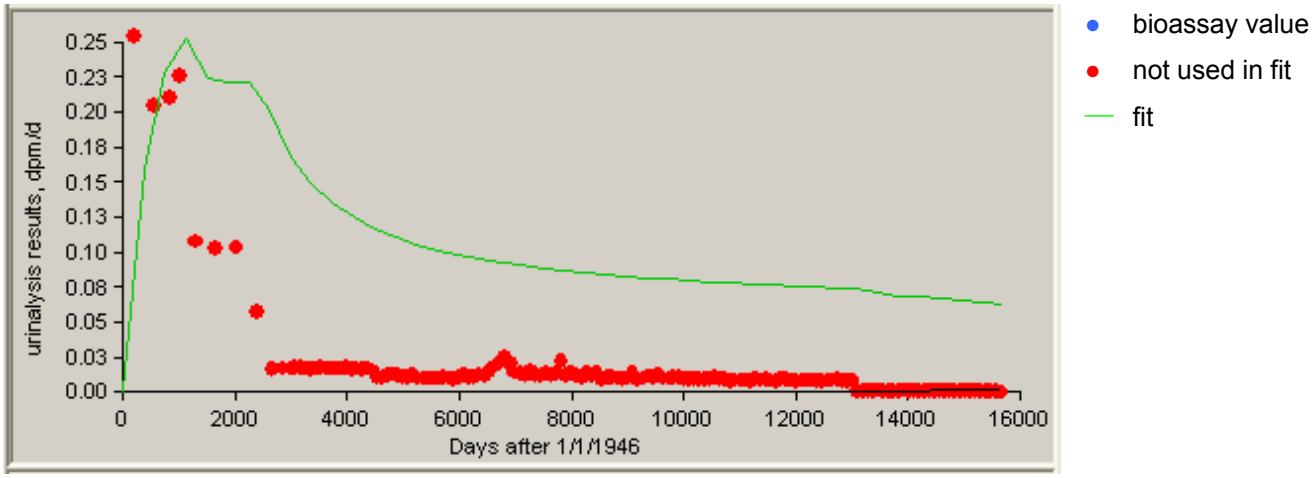

Figure A-5. Predicted 50th-percentile urinary excretion of Type M plutonium from 1946 to 1988 based on four independent intakes, compared to bioassay data.

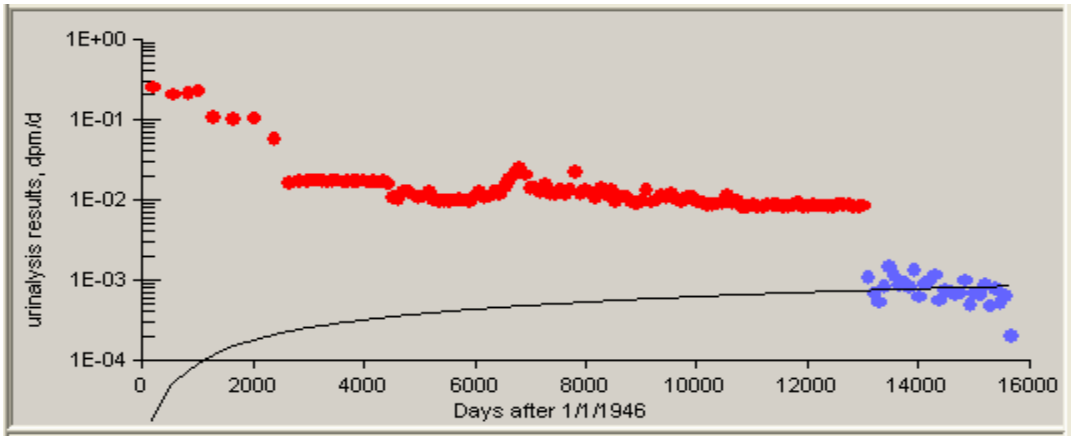

Figure A-6. 50th-percentile plutonium urinalysis data for intakes of Type S material, 1946 to 1988.

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Table A-2. Statistical summary of uranium 24-hr urinary excretion rates, 1948-1988[a].

Effective bioassay date	GM[b] (50th) µg/d	GM*GSD[c] (84th) µg/d
04/01/1948	3.88	12.48
10/1/1948	5.50	21.41
02/15/1949	4.20	15.22
05/15/1949	3.32	10.87
08/15/1949	7.02	20.71
11/15/1949	4.65	15.47
02/15/1950	6.97	23.35
05/15/1950	4.57	15.20
08/15/1950	4.71	13.26
11/15/1950	3.62	11.81
02/15/1951	3.97	13.61
05/15/1951	4.15	14.93
08/15/1951	4.51	16.53
11/15/1951	4.15	13.99
02/15/1952	5.71	20.24
05/15/1952	4.84	16.17
08/15/1952	4.48	14.71
11/15/1952	5.15	16.08
02/15/1953	4.89	15.49
05/15/1953	4.07	12.44
08/15/1953	3.39	10.92
11/15/1953	3.62	12.79
02/15/1954	3.02	9.77
05/15/1954	3.02	9.26
08/15/1954	3.16	10.11
11/15/1954	3.78	12.74
2/14/1955	3.17	9.87
05/15/1955	3.44	11.06
08/15/1955	2.77	8.14
11/15/1955	3.21	10.35
2/14/1956	2.61	7.45
05/15/1956	3.55	11.48
08/15/1956	4.20	14.94
11/15/1956	2.88	8.92
02/15/1957	4.28	15.51
05/15/1957	5.70	21.26
08/15/1957	6.23	23.63
11/51/1957	6.88	24.31
02/15/1958	6.65	22.18
05/15/1958	5.34	18.07
08/15/1958	4.34	14.70
11/15/1958	3.96	12.54
02/15/1959	3.94	12.97
05/15/1959	4.59	15.29
08/15/1959	5.54	19.18
11/15/1959	4.48	16.23
02/15/1960	4.20	14.36
05/15/1960	5.82	20.97
08/15/1960	4.47	14.79
11/15/1960	4.34	15.45
02/15/1961	4.76	18.96
05/15/1961	4.85	17.54
08/15/1961	3.76	11.26
11/15/1961	3.86	11.32
02/15/1962	3.68	11.21
05/15/1962	3.05	8.70
08/15/1962	2.78	7.73
11/15/1962	2.74	7.69
02/15/1963	3.77	10.83
05/15/1963	3.19	8.55
08/15/1963	2.73	7.43
11/15/1963	2.76	7.37
02/15/1964	2.39	6.25
05/15/1964	2.54	6.79
08/15/1964	2.89	9.30
11/15/1964	2.66	7.54
02/15/1965	3.56	11.55
05/15/1965	3.82	13.26
08/15/1965	4.39	16.82
11/15/1965	3.72	11.94
02/15/1966	3.09	10.22
05/15/1966	3.02	9.28
08/15/1966	3.56	12.10
11/15/1966	3.13	9.35
02/15/1967	2.85	8.54
05/15/1967	2.97	8.84
08/15/1967	2.71	7.71
11/15/1967	2.77	8.13
02/15/1968	3.06	9.14
05/15/1968	3.73	11.62
08/15/1968	2.96	8.82
11/15/1968	3.21	9.10
02/15/1969	2.38	5.98
05/15/1969	2.73	7.06
08/15/1969	2.48	6.26
11/15/1969	2.27	5.67
07/01/1970	2.24	5.65
07/01/1971	2.61	6.88
07/01/1972	3.10	8.19
07/01/1973	2.27	5.34
07/01/1974	2.86	8.96
07/01/1975	0.97	5.99
07/01/1976	0.79	4.84
07/01/1977	0.39	1.42
07/01/1978	0.25	0.76
07/01/1979	0.29	0.96
07/01/1980	0.25	0.74
07/01/1981	0.41	2.02
07/01/1982	0.36	2.11
07/01/1983	0.13	0.64
02/15/1984	0.14	0.82
05/15/1984	0.20	0.78
08/15/1984	0.25	1.15
11/15/1984	0.32	1.34
02/15/1985	0.31	1.25
05/15/1985	0.28	0.89
08/15/1985	0.23	0.71
11/15/1985	0.15	0.45
02/15/1986	0.13	0.38
05/15/1986	0.27	1.36
08/15/1986	0.21	0.78
11/15/1986	0.18	0.62
02/15/1987	0.12	0.43
05/15/1987	0.15	0.50
08/15/1987	0.14	0.42
11/15/1987	0.15	0.43
02/15/1988	0.14	0.41
05/15/1988	0.09	0.23
08/15/1988	0.09	0.29
11/15/1988	0.02	0.30

a. Through 1981, excretion was converted to µg/d from µg/L assuming 1.4L/d excretion.
b. GM = geometric mean or 50th-percentile value of the fitted line.
c. GSD = geometric standard deviation; GM*GSD is the 84th-percentile value of the fitted line.

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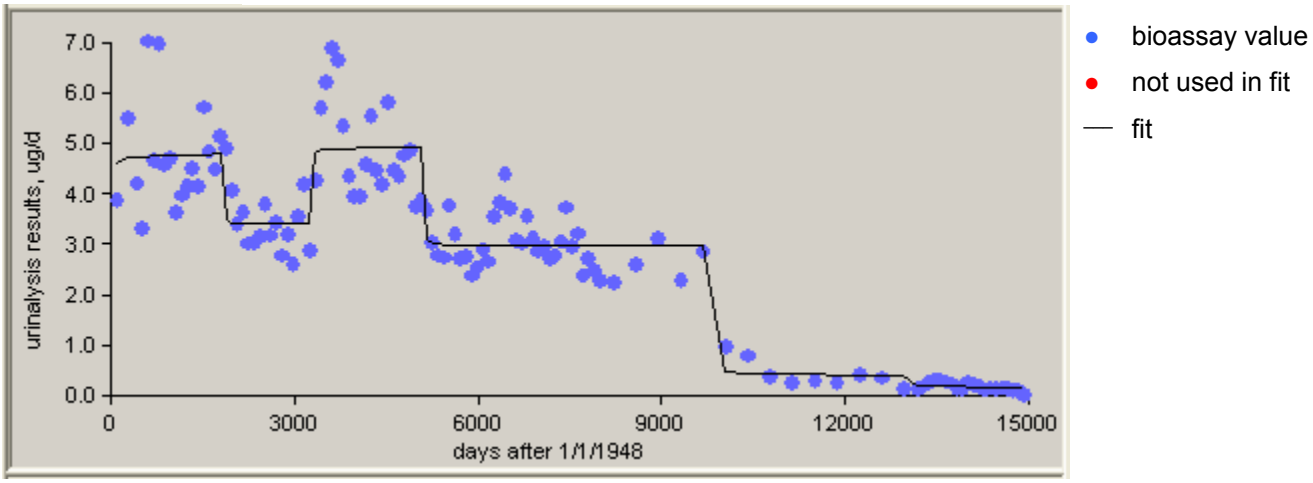

Figure A-7. 50th-percentile uranium urinalysis data for intakes of Type F material, 1948 to 1988.

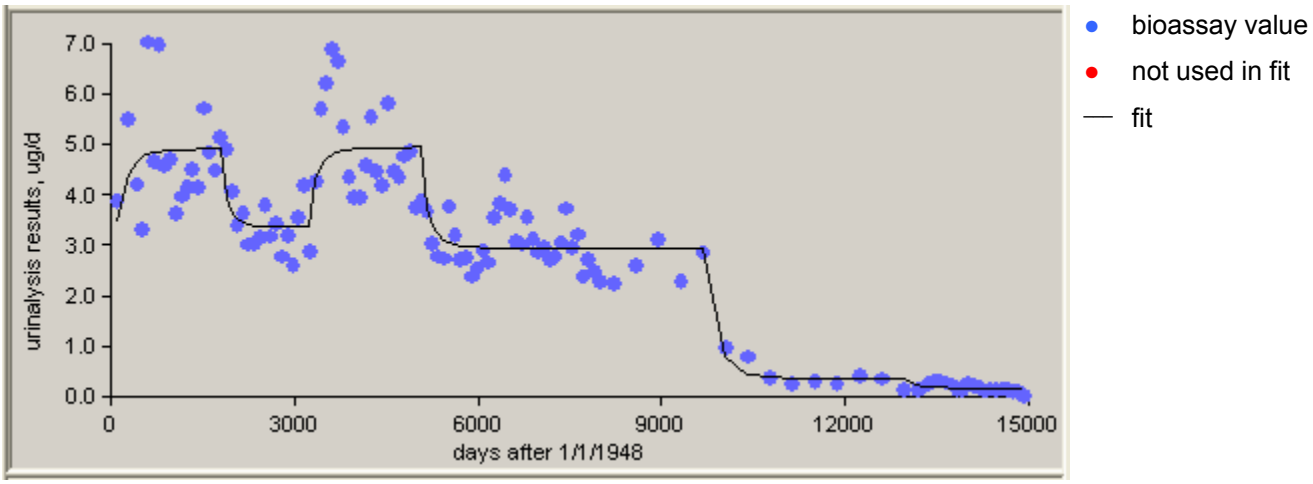

Figure A-8. 50th-percentile uranium urinalysis data for intakes of Type M material, 1948 to 1988.

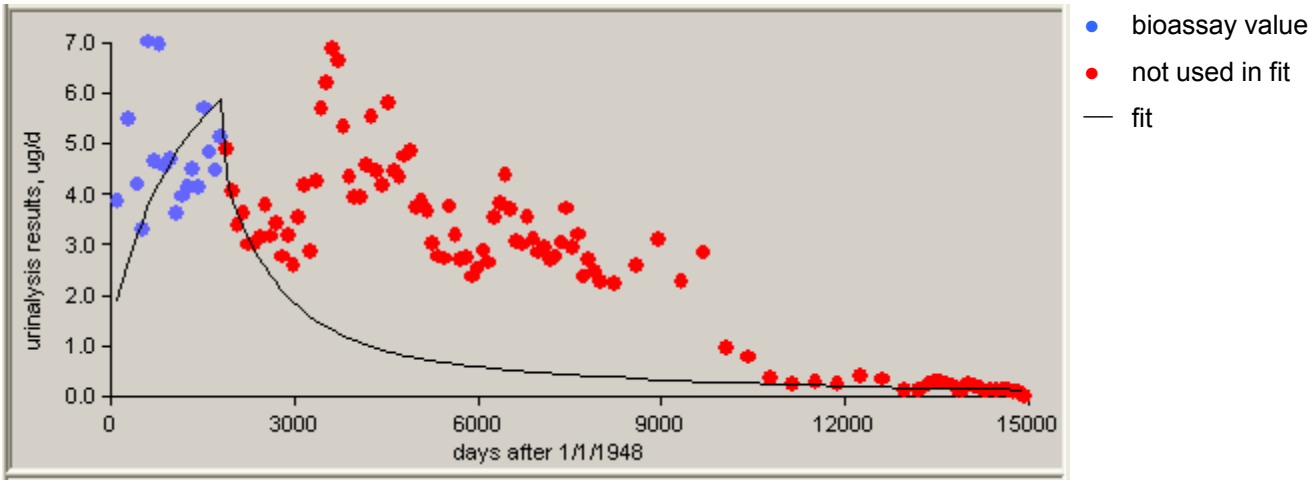

Figure A-9. 50th-percentile uranium urinalysis data for intakes of Type S material, 1948 to 1952.

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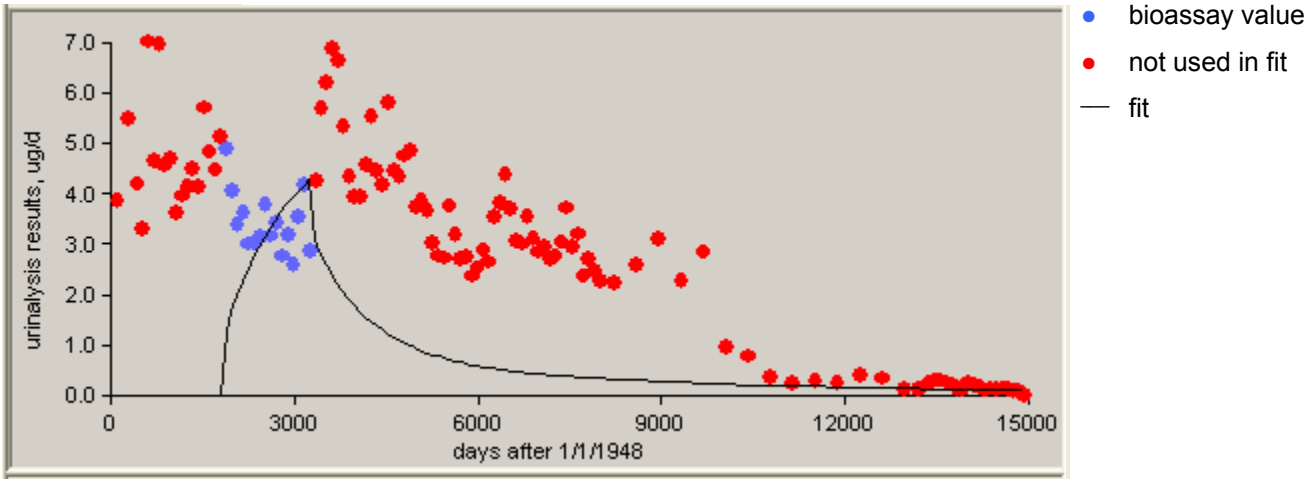

Figure A-10. 50th-percentile uranium urinalysis data for intakes of Type S material, 1953 to 1956.

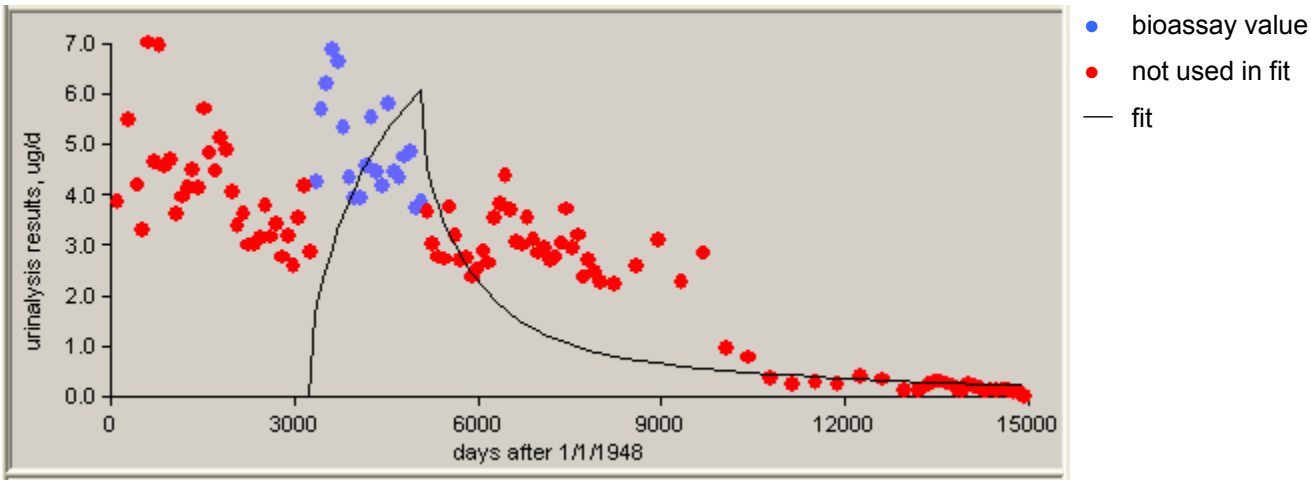

Figure A-11. 50th-percentile uranium urinalysis data for intakes of Type S material, 1957 to 1961.

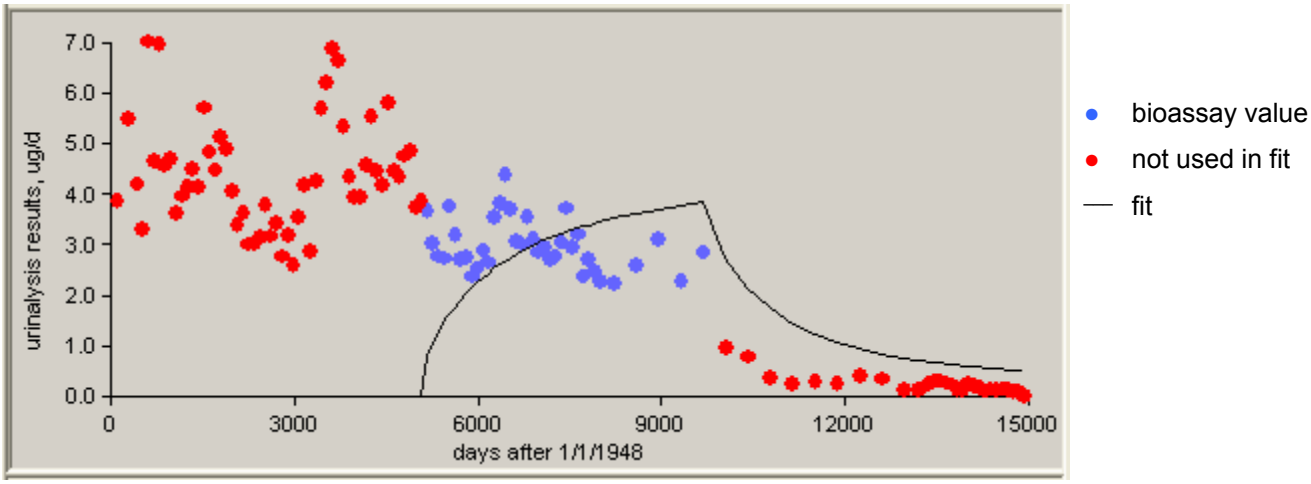

Figure A-12. 50th-percentile uranium urinalysis data for intakes of Type S material, 1962 to 1974.

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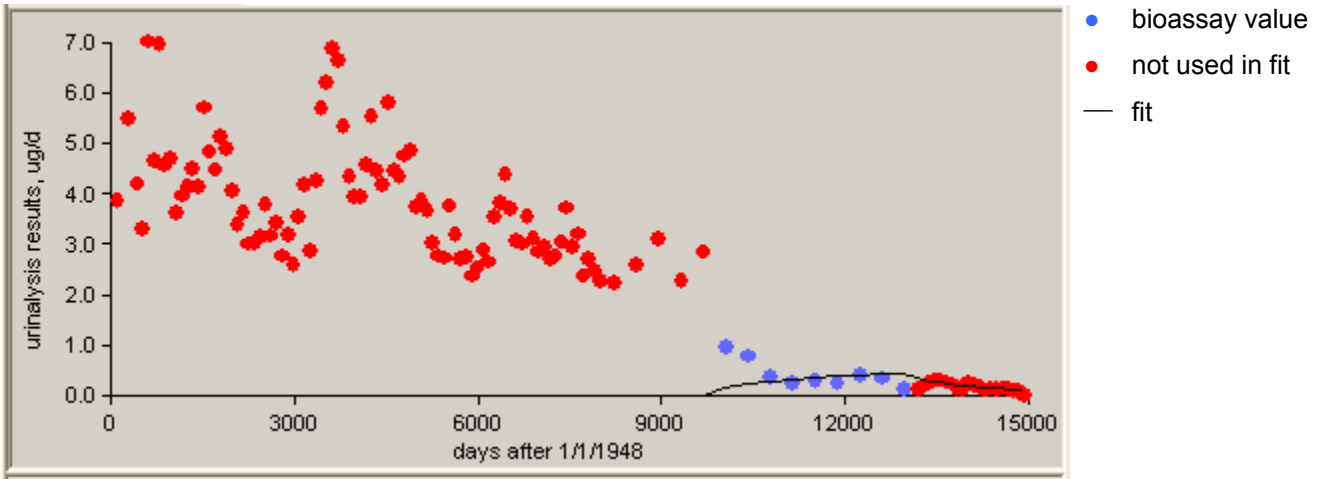

Figure A-13. 50th-percentile uranium urinalysis data for intakes of Type S material, 1975 to 1983.

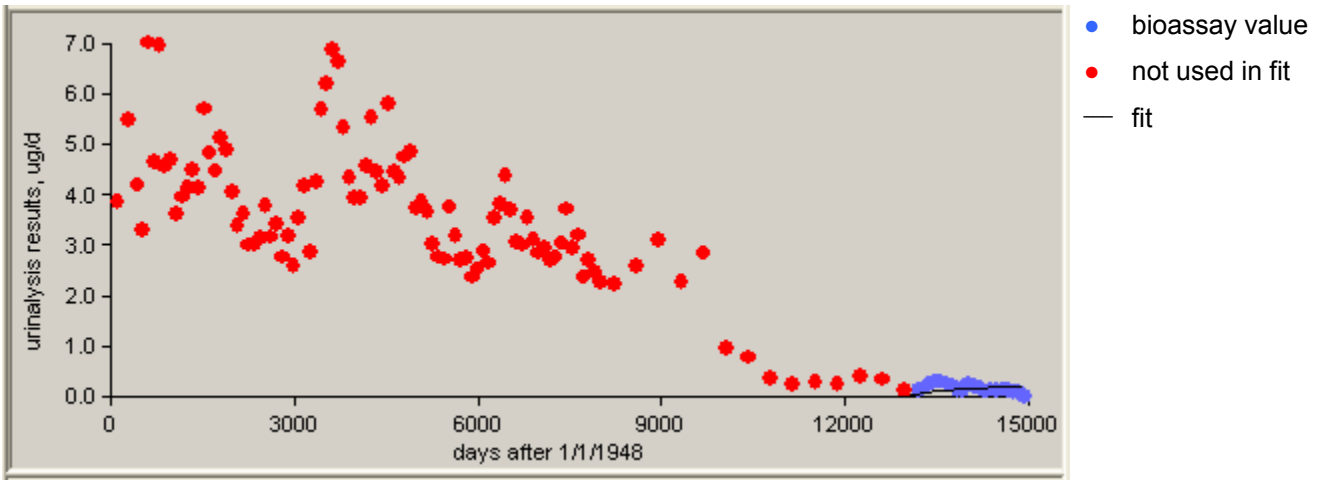

Figure A-14. 50th-percentile uranium urinalysis data for intakes of Type S material, 1984 to 1988.

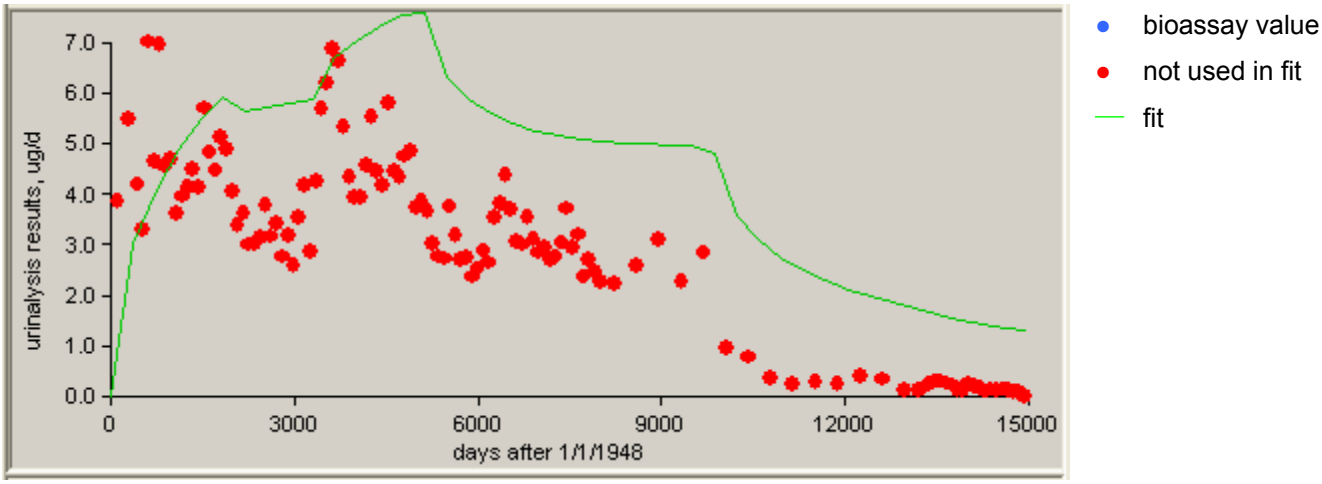

Figure A-15. Predicted 50th-percentile urinary excretion of Type S uranium from 1946 to 1988 based on six independent intakes, compared to bioassay data.

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Table A-3. Statistical summary of ^{90}Sr 24-hr urinary excretion rates, 1965-1988.

Effective bioassay date	GM (50th) dpm/d	GM*GSD (84th) dpm/d
07/01/1966	20.74	56.46
07/01/1969	14.53	55.88
07/01/1971	1.76	4.56
07/01/1972	2.33	12.27
07/01/1973	1.64	4.51
07/01/1974	1.38	3.82
07/01/1975	0.923	2.57
07/01/1976	1.20	3.40
07/01/1977	0.835	2.12
07/01/1978	1.009	3.82
02/15/1979	0.882	2.55
08/15/1979	2.00	5.58
07/01/1980	1.92	4.92
07/01/1981	2.33	7.60
02/15/1982	0.289	1.43
05/15/1982	0.322	1.58
08/15/1982	0.350	1.72
11/15/1982	0.802	7.91
02/15/1983	0.665	2.60
05/15/1983	0.387	3.13
08/15/1983	0.743	3.78
11/15/1983	0.410	2.73
02/15/1984	0.807	1.76
05/15/1984	1.04	2.70
08/15/1984	1.00	1.66
11/15/1984	1.06	1.87
02/15/1985	1.30	2.88
05/15/1985	1.18	2.38
08/15/1985	1.06	1.69
11/15/1985	1.11	2.20
02/15/1986	1.12	2.26
05/15/1986	1.05	1.88
08/15/1986	1.14	2.05
11/15/1986	1.27	2.29
02/15/1987	1.28	2.02
05/15/1987	1.43	2.28
08/15/1987	1.43	2.18
11/15/1987	1.47	2.21
02/15/1988	1.79	2.79
05/15/1988	1.53	2.57
08/15/1988	1.32	2.02
11/15/1988	0.327	0.993

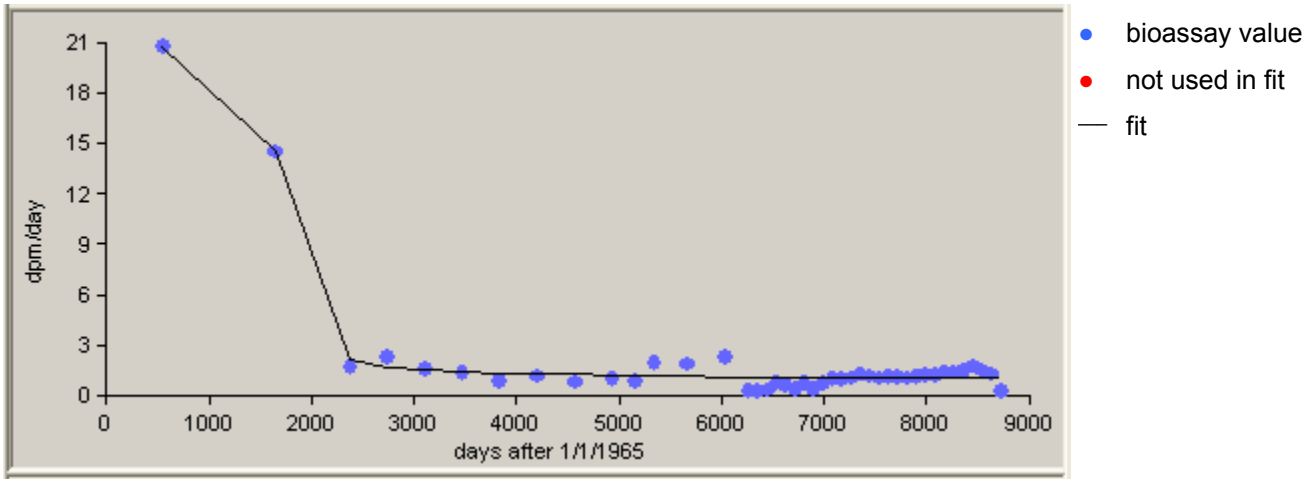

Figure A-16. 50th-percentile strontium urinalysis data for intakes of Type F material, 1965 to 1988.

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Table A-4. Statistical summary of ^{147}Pm 24-hr urinary excretion rates, 1966-1979.

Effective bioassay date	GM (50th) dpm/d	GM*GSD (84th) dpm/d
01/01/1967	25.7	82.9
2/12/1969	28.6	88.5
02/15/1971	13.7	35.6
07/01/1977[a]	10.5	27.4

a. Very few bioassays were obtained during 1972 through 1974 so no statistics were developed. A single intake rate was fit for 1970 through 1979, using the 1971 and 1977 statistical values.

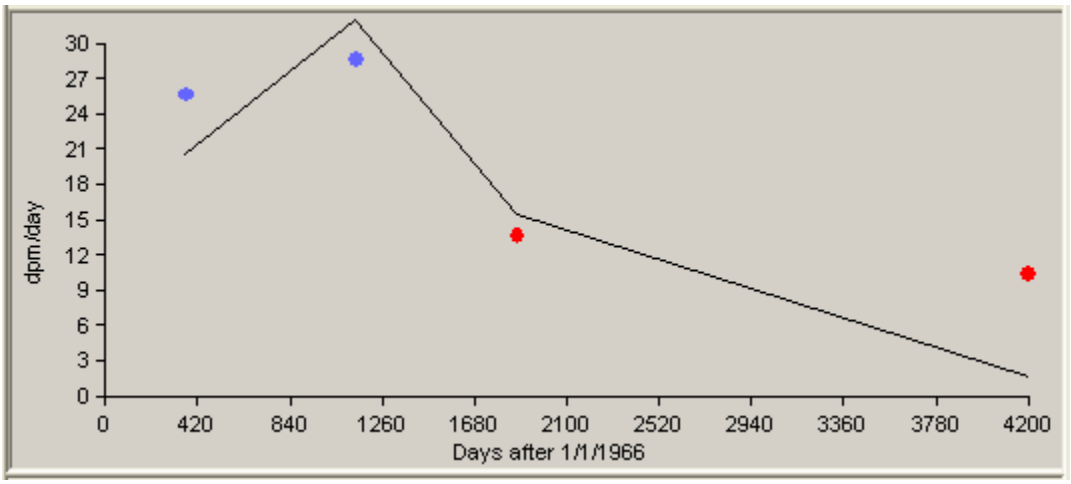

Figure A-17. 50th-percentile promethium urinalysis data for intakes of Type M material, 1966 to 1969.

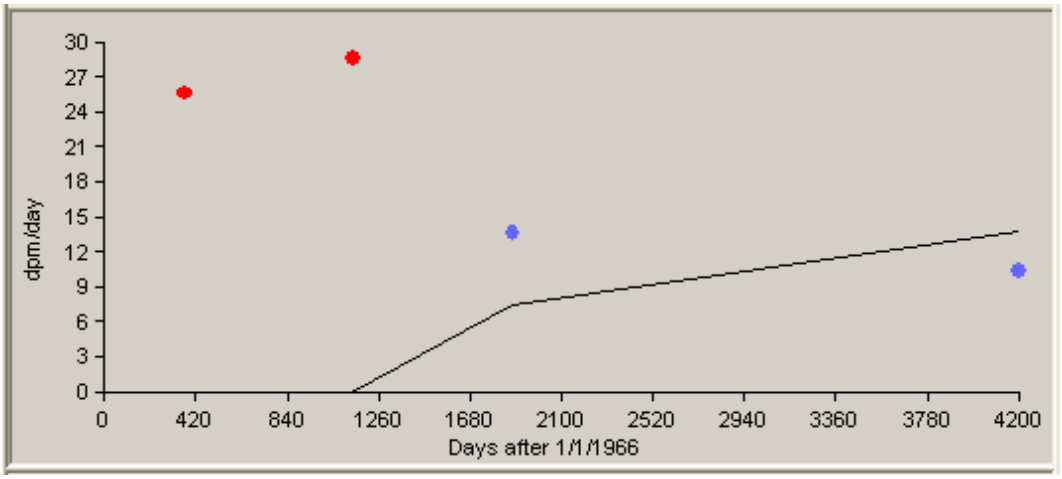

Figure A-18. 50th-percentile promethium urinalysis data for intakes of Type M material, 1970 to 1979.

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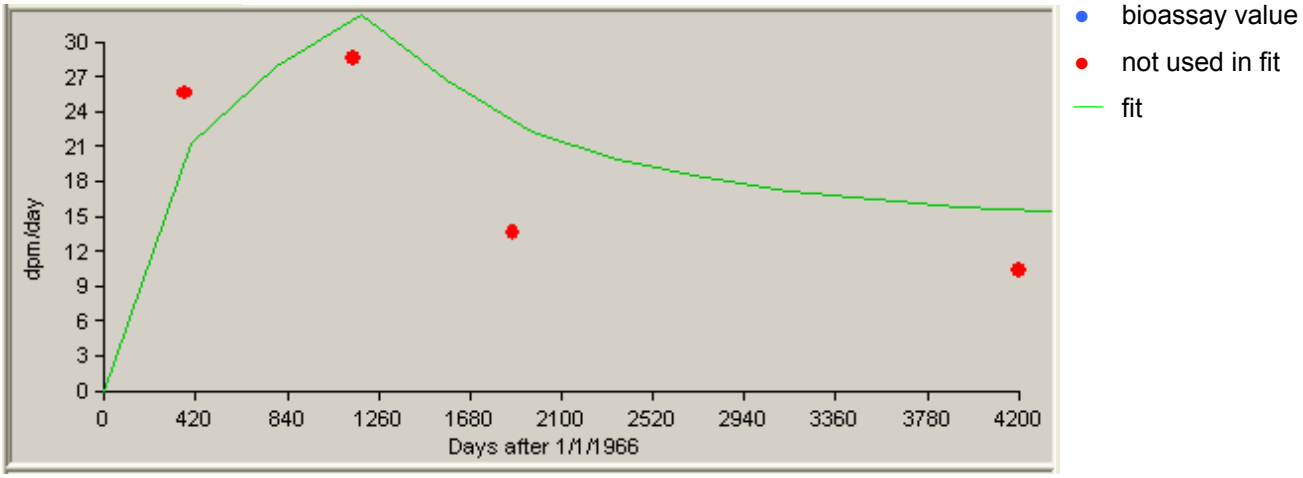

Figure A-19. Predicted 50th-percentile urinary excretion of Type M promethium from 1966 to 1979 based on two independent intakes, compared to bioassay data.

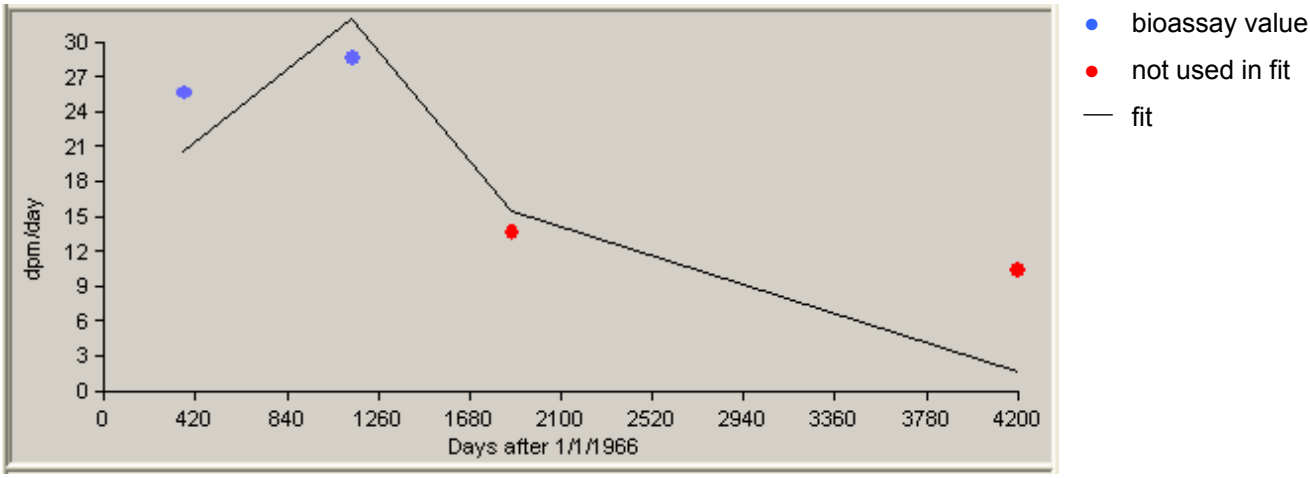

Figure A-20. 50th-percentile promethium urinalysis data for intakes of Type S material, 1966 to 1969.

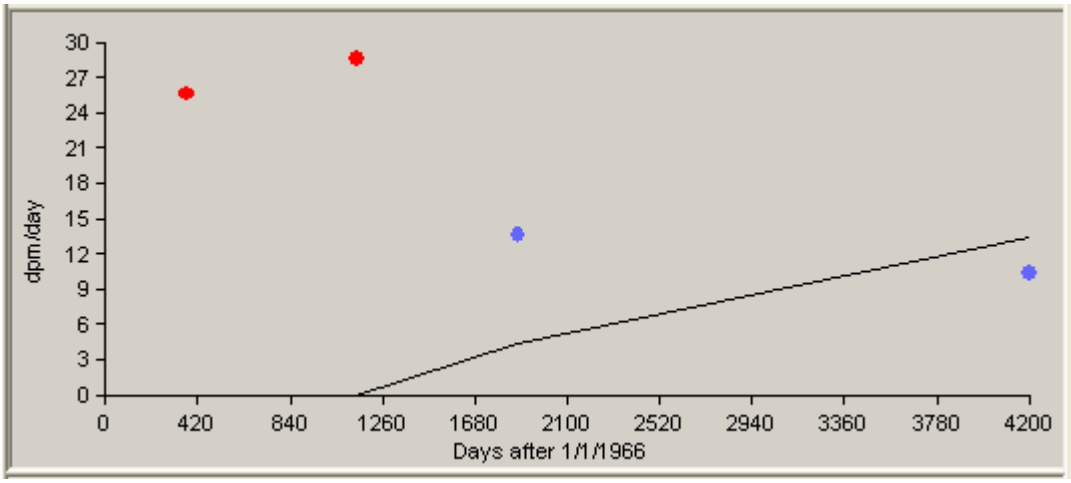

Figure A-21. 50th-percentile promethium urinalysis data for intakes of Type S material, 1970 to 1979.

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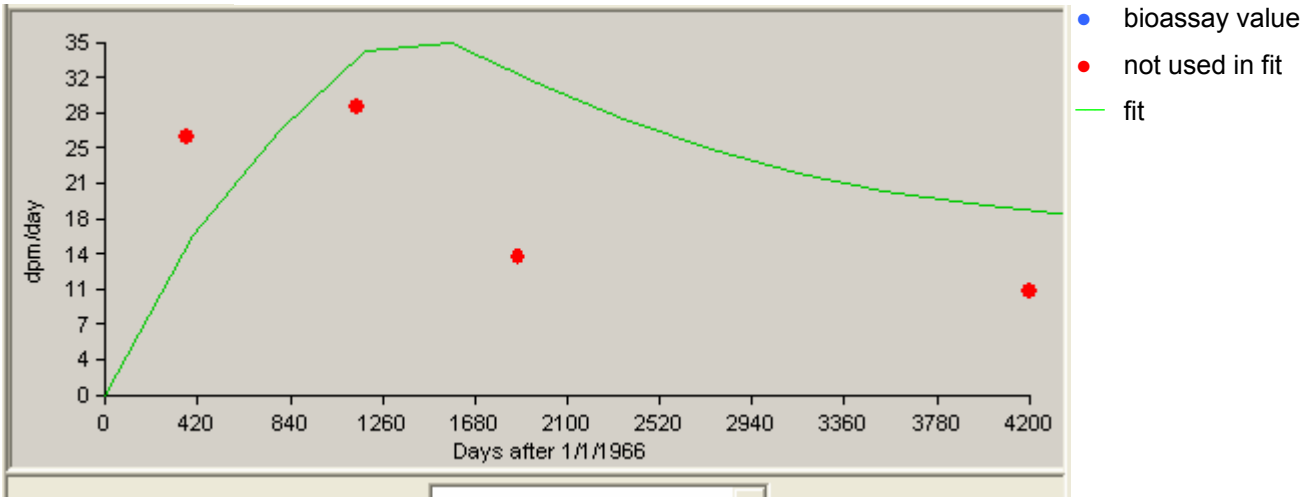

Figure A-22. Predicted 50th-percentile urinary excretion of Type S promethium from 1966 to 1979 based on two independent intakes, compared to bioassay data.

Table A-5. Statistical summary of ^{65}Zn measured in whole-body counts.

Effective bioassay date	GM (50th) nCi	GM*GSD (84th) nCi
07/01/1960	2.45	7.80
04/01/1961	2.16	9.58
10/1/1961	2.13	7.78
04/01/1962	2.04	8.73
10/1/1962	2.15	12.08
02/15/1963	2.11	8.44
05/15/1963	1.60	6.25
08/15/1963	1.34	4.70
11/15/1963	3.40	12.52
02/15/1964	2.40	9.02
05/15/1964	2.12	7.22
08/15/1964	1.92	6.79
11/15/1964	4.20	16.06
02/15/1965	2.93	12.17
05/15/1965	3.11	10.80
08/15/1965	2.348	9.40
11/15/1965	2.56	10.10
02/15/1966	2.82	9.32
05/15/1966	2.87	10.10
08/15/1966	1.84	6.32
11/15/1966	1.86	8.03
02/15/1967	1.78	6.06
05/15/1967	3.35	12.02
08/15/1967	2.13	8.26
11/15/1967	1.50	5.91
02/15/1968	1.53	6.61
05/15/1968	1.38	5.45
08/15/1968	1.41	6.18
11/15/1968	1.83	6.78
02/15/1969	2.35	7.89
05/15/1969	1.28	4.63
08/15/1969	1.05	3.66
11/15/1969	1.45	5.37
02/15/1970	1.45	5.56
05/15/1970	1.27	4.31
08/15/1970	1.56	5.11
11/15/1970	2.10	5.87
02/15/1971	1.52	5.06
05/15/1971	1.55	4.69
08/15/1971	1.29	3.81
11/15/1971	1.24	3.55
02/15/1972	1.18	3.92
05/15/1972	0.963	3.01
08/15/1972	1.17	3.74
11/15/1972	1.18	3.98
02/15/1973	1.18	4.21
05/15/1973	1.04	3.44
08/15/1973	0.612	1.99
11/15/1973	0.678	2.27
02/15/1974	0.497	1.61
05/15/1974	0.431	1.33
08/15/1974	0.456	1.41
11/15/1974	0.507	1.64
04/01/1975	0.405	1.23
10/1/1975	0.613	2.00
02/15/1976	0.647	2.19
05/15/1976	0.712	3.25
08/15/1976	0.673	2.46
11/15/1976	1.21	5.39
02/15/1977	0.964	3.74
05/15/1977	0.788	2.83
08/15/1977	0.688	2.67
11/15/1977	0.388	1.27
02/15/1978	0.371	1.16
05/15/1978	0.369	1.15
08/15/1978	0.373	1.19
11/15/1978	0.396	1.28
02/15/1979	0.401	1.28
05/15/1979	0.415	1.37
08/15/1979	0.348	1.02
11/15/1979	0.406	1.31
02/15/1980	0.384	1.19
05/15/1980	0.403	1.32
08/15/1980	0.372	1.15
11/15/1980	0.348	1.01
02/15/1981	0.372	1.09
05/15/1981	0.354	1.04
08/15/1981	0.306	0.817
11/15/1981	0.316	0.854
02/15/1982	0.340	0.947
05/15/1982	0.338	0.944
08/15/1982	0.334	0.934
11/15/1982	0.331	0.909
02/15/1983	0.323	0.884
05/15/1983	0.334	0.922
08/15/1983	0.314	0.843
11/15/1983	0.337	0.937
04/01/1984	0.354	1.03
10/01/1984	0.391	1.09

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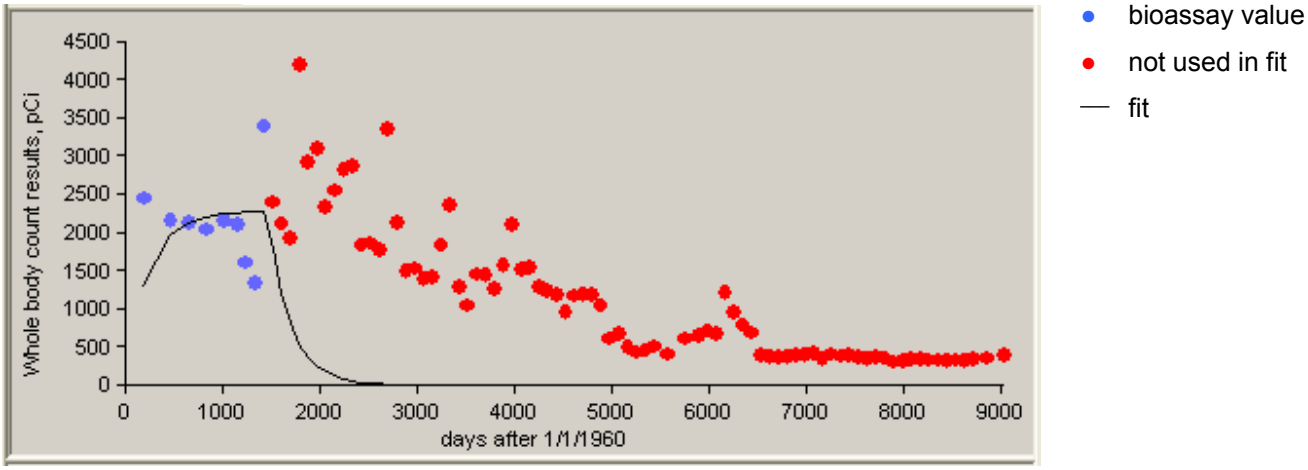

Figure A-23. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1960 to 1963.

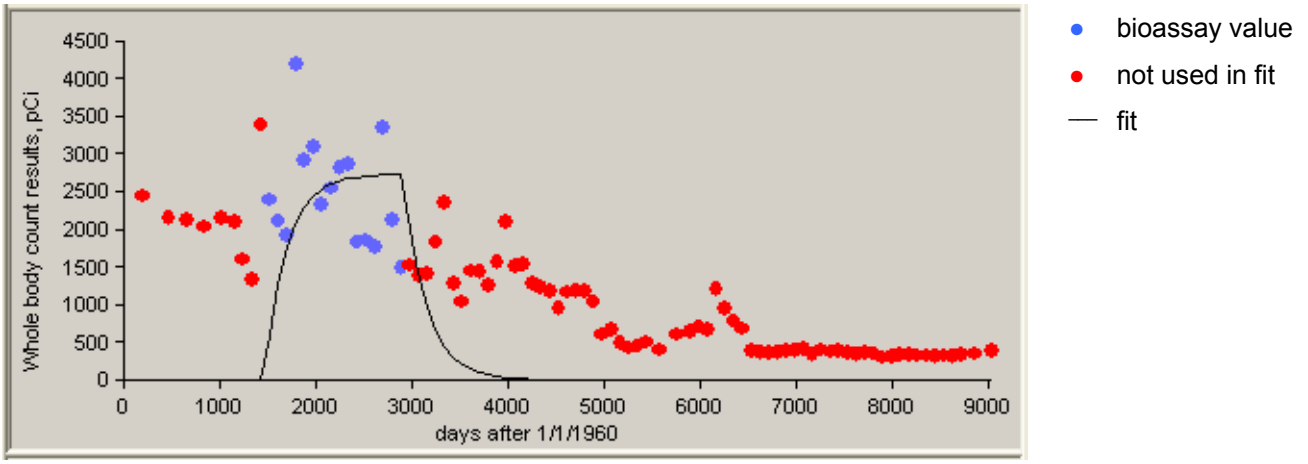

Figure A-24. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1964 to 1967.

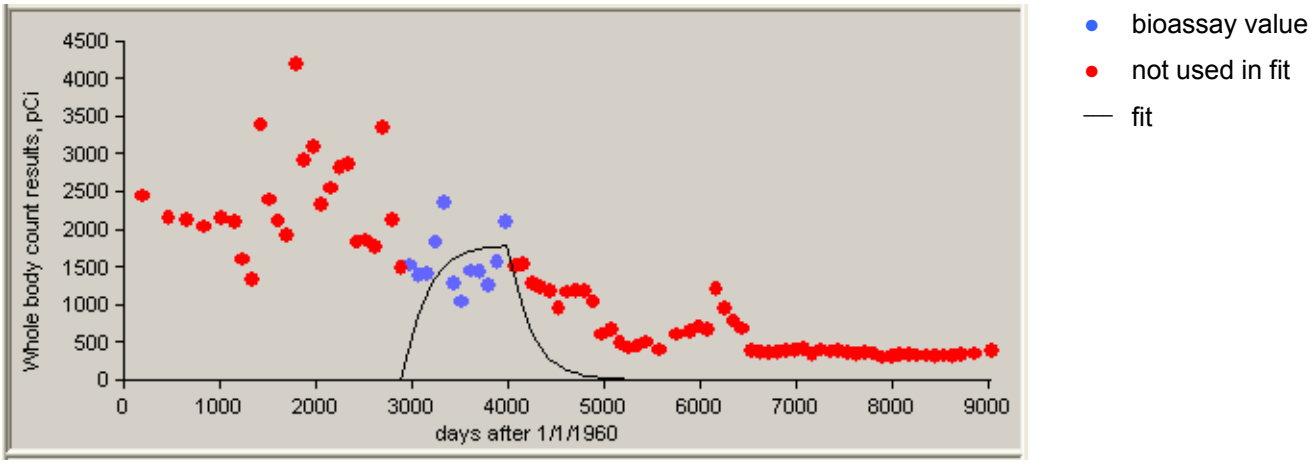

Figure A-25. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1968 to 1970.

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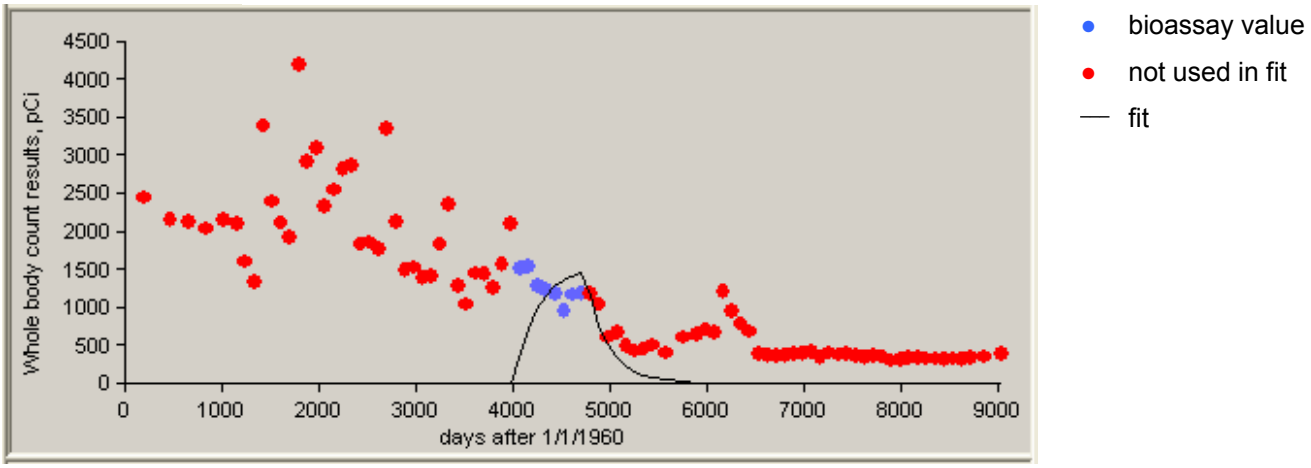

Figure A-26. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1971 to 1972.

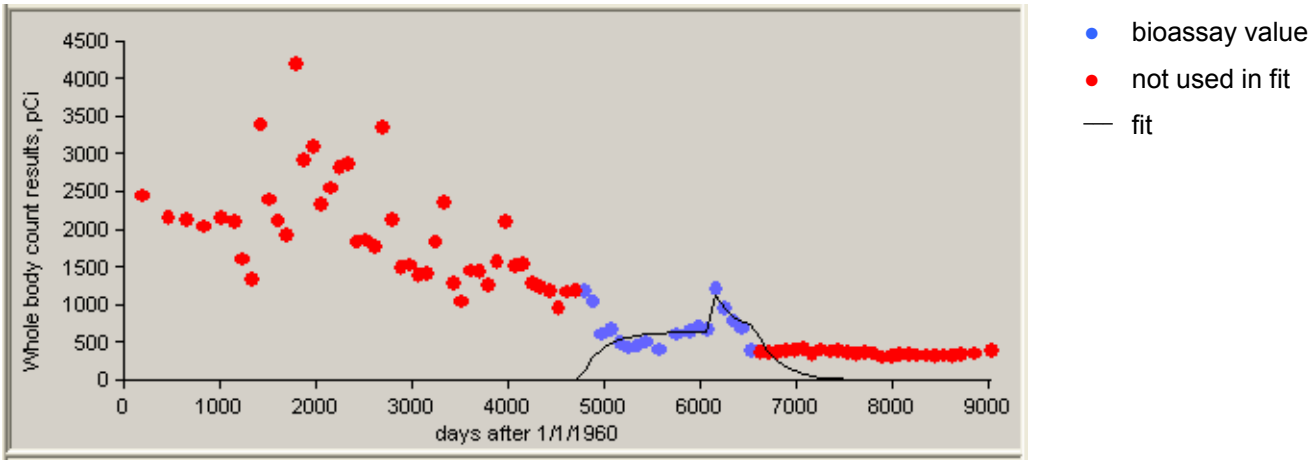

Figure A-27. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1973 to 1977.

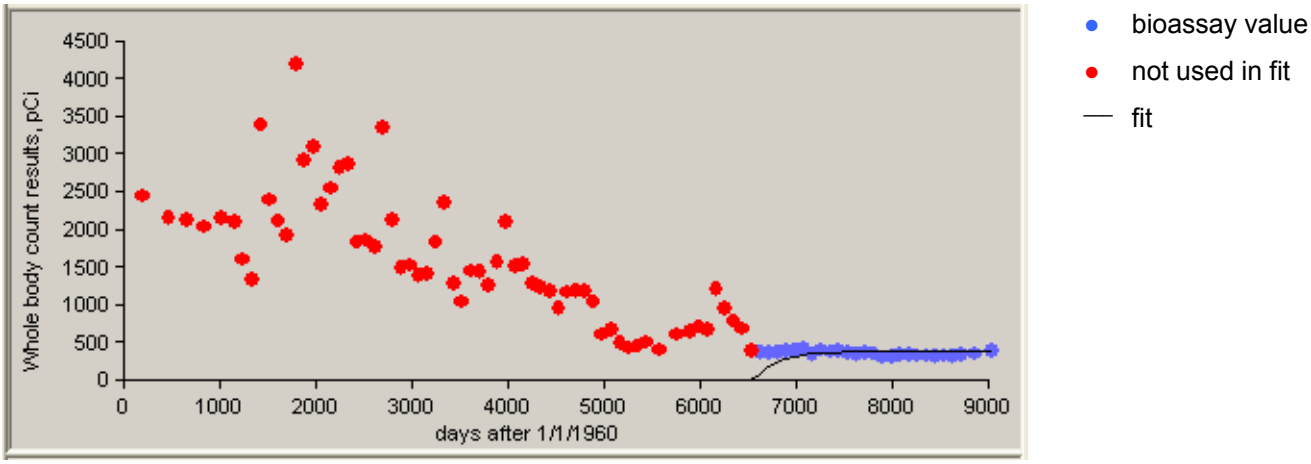

Figure A-28. 50th-percentile zinc whole-body counting data for inhalation intakes of Type S material, 1978 to 1984.

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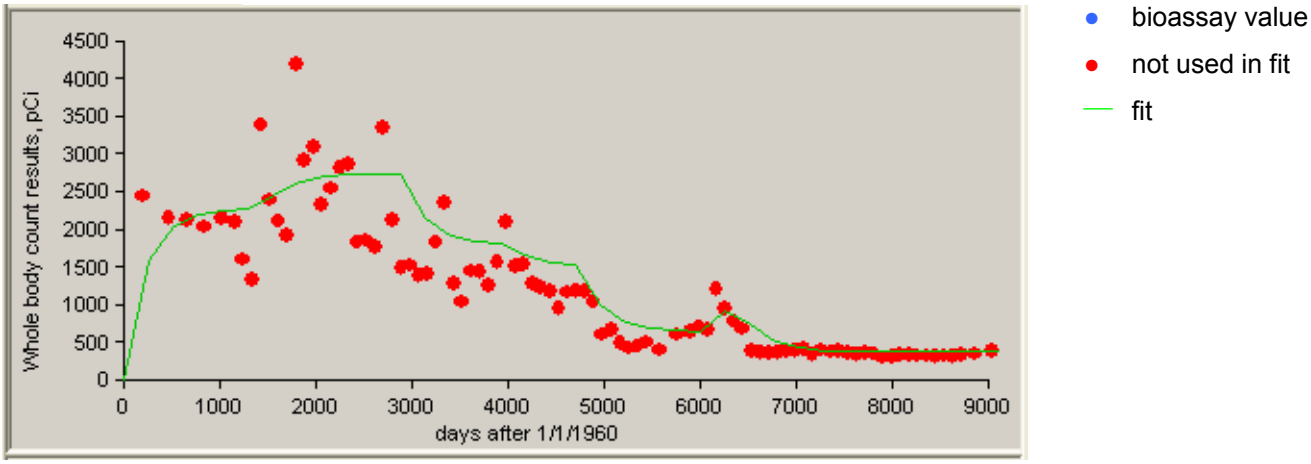

Figure A-29. Predicted 50th-percentile urinary excretion of inhaled Type S zinc from 1960 to 1984 based on six independent chronic intakes and one acute intake, compared to bioassay data.

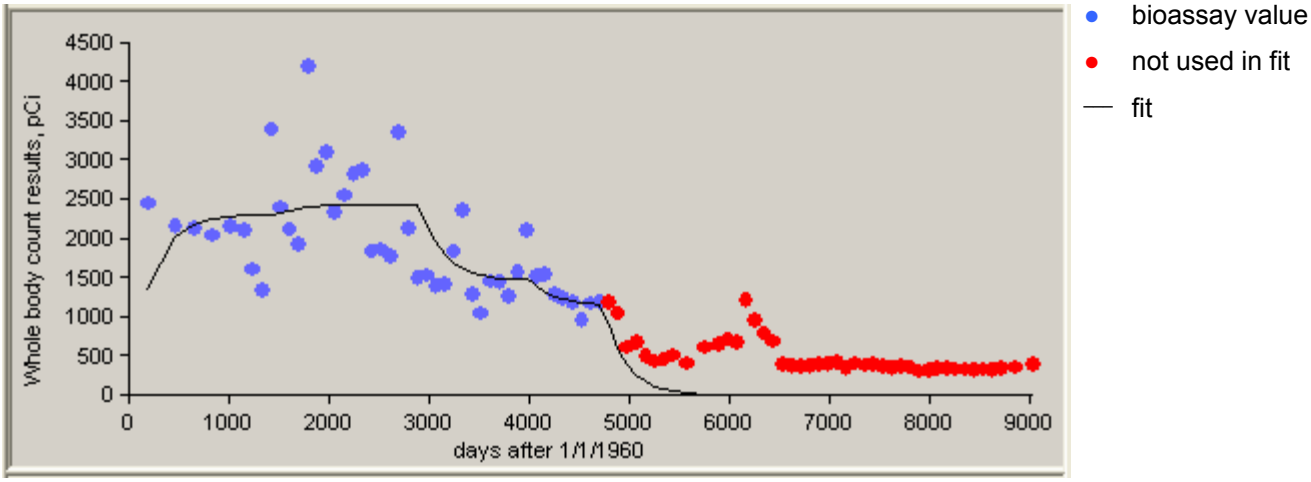

Figure A-30. 50th-percentile zinc whole-body counting data for ingestion intakes, 1960 to 1984.

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Table A-6. Statistical summary of ^{24}Na measured in whole-body counts.

Effective bioassay date	GM (50th) nCi	GM*GSD (84th) nCi
07/01/1960	0.221	0.587
04/01/1961	0.174	0.610
10/1/1961	0.187	0.616
02/15/1962	0.142	0.421
05/15/1962	0.182	0.609
08/15/1962	0.150	0.413
11/15/1962	0.145	0.414
02/15/1963	0.180	0.562
05/15/1963	0.185	0.515
08/15/1963	0.231	0.713
11/15/1963	1.11	4.02
02/15/1964	0.388	1.35
05/15/1964	0.355	1.16
08/15/1964	0.316	0.993
11/15/1964	0.647	2.06
02/15/1965	0.555	2.17
05/15/1965	0.295	0.983
08/15/1965	0.286	0.930
11/15/1965	0.292	0.891
02/15/1966	0.347	1.09
05/15/1966	0.233	0.650
08/15/1966	0.257	0.834
11/15/1966	0.218	0.687
02/15/1967	0.288	0.904
05/15/1967	0.428	1.740
08/15/1967	0.247	0.701
11/15/1967	0.346	0.998
02/15/1968	0.405	1.610
05/15/1968	0.269	0.887
08/15/1968	0.229	0.728
11/15/1968	0.256	0.805
02/15/1969	0.194	0.570
05/15/1969	0.204	0.649
08/15/1969	0.268	0.915
11/15/1969	0.285	0.979
02/15/1970	0.218	0.623
05/15/1970	0.228	0.605
08/15/1970	0.193	0.543
11/15/1970	0.196	0.559
02/15/1971	0.260	0.711
05/15/1971	0.234	0.591
08/15/1971	0.224	0.589
11/15/1971	0.220	0.591
02/15/1972	0.245	0.715
05/15/1972	0.255	0.760
08/15/1972	0.206	0.608
11/15/1972	0.243	0.673
02/15/1973	0.244	0.756
05/15/1973	0.196	0.556
08/15/1973	0.220	0.614
11/15/1973	0.176	0.501
02/15/1974	0.144	0.401
05/15/1974	0.147	0.431
08/15/1974	0.149	0.418
11/15/1974	0.139	0.369
02/15/1975	0.128	0.331
05/15/1975	0.131	0.340
08/15/1975	0.140	0.383
11/15/1975	0.131	0.342
02/15/1976	0.139	0.371
05/15/1976	0.148	0.404
08/15/1976	0.166	0.459
11/15/1976	0.158	0.434
02/15/1977	0.168	0.465
05/15/1977	0.166	0.466
08/15/1977	0.162	0.449
11/15/1977	0.162	0.458
02/15/1978	0.138	0.368
05/15/1978	0.148	0.401
08/15/1978	0.139	0.368
11/15/1978	0.150	0.414
02/15/1979	0.134	0.356
05/15/1979	0.155	0.421
08/15/1979	0.147	0.396
11/15/1979	0.145	0.387
02/15/1980	0.139	0.369
05/15/1980	0.140	0.372
08/15/1980	0.131	0.346
11/15/1980	0.140	0.370
02/15/1981	0.139	0.372
05/15/1981	0.138	0.366
08/15/1981	0.147	0.403
11/15/1981	0.133	0.348
02/15/1982	0.134	0.352
05/15/1982	0.149	0.407
08/15/1982	0.140	0.375
11/15/1982	0.143	0.387
02/15/1983	0.145	0.399
05/15/1983	0.142	0.385
08/15/1983	0.142	0.390
11/15/1983	0.150	0.414
04/01/1984	0.144	0.377
10/01/1984	0.171	0.495

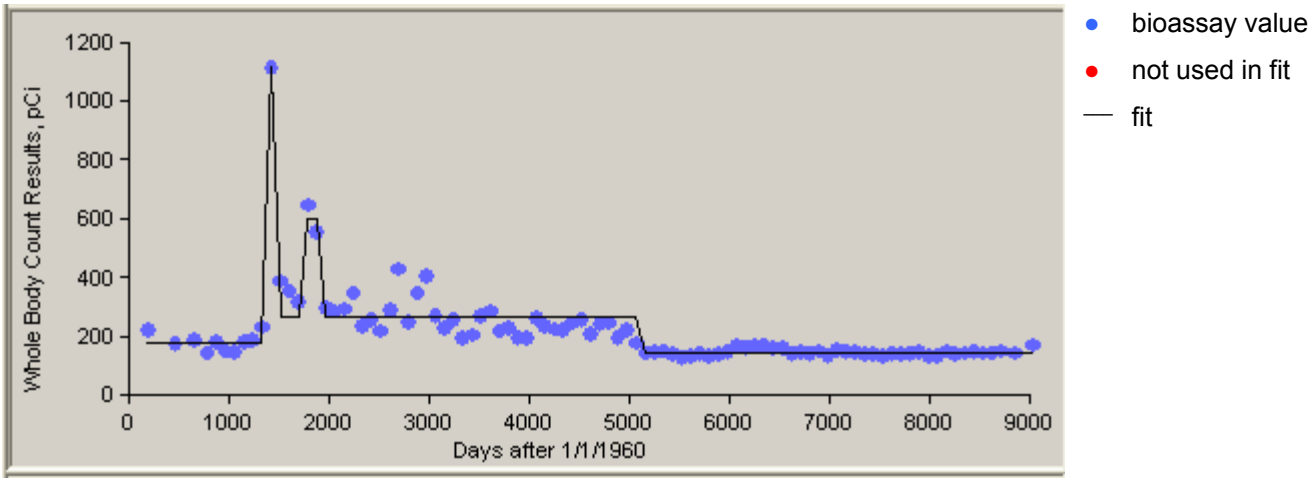

Figure A-31. 50th-percentile sodium whole-body counting data for inhalation intakes of Type F material, 1960 to 1984.

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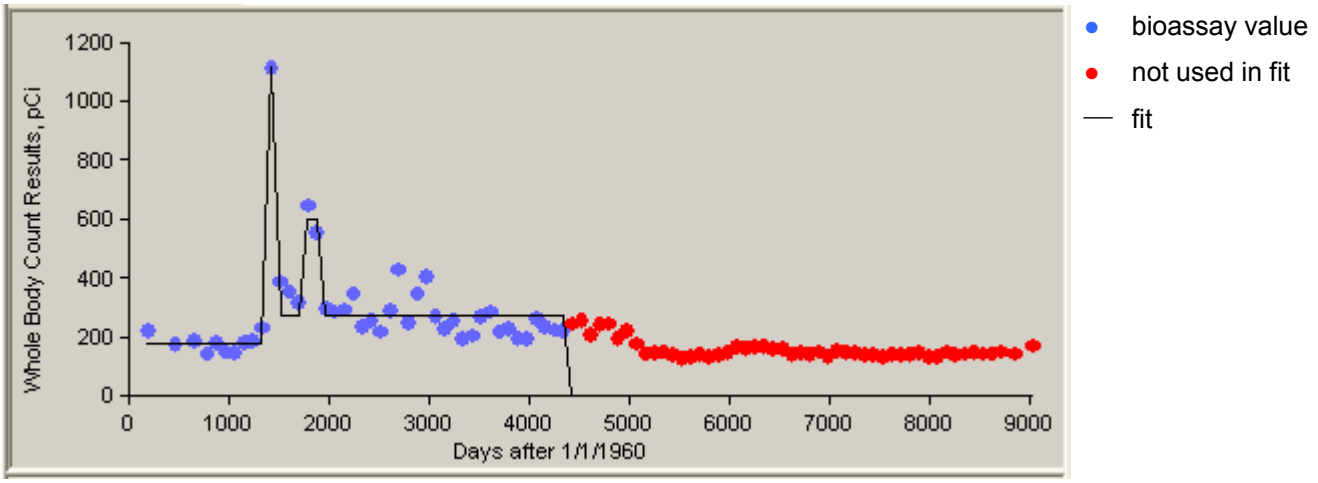

Figure A-32. 50th-percentile sodium whole-body counting data for ingestion intakes, 1960 to 1984.

Table A-7. Statistical summary of ^{137}Cs measured in whole-body counts.

Effective bioassay date	GM (50th) nCi	GM*GSD (84th) nCi
02/15/1960	6.773	9.620
05/15/1960	6.689	9.347
08/15/1960	5.977	9.466
11/15/1960	5.770	8.302
02/15/1961	4.728	6.858
05/15/1961	4.482	6.764
08/15/1961	3.805	6.006
11/15/1961	3.491	5.184
02/15/1961	3.527	5.563
05/15/1961	3.457	5.055
08/15/1961	4.378	6.502
11/15/1961	5.253	7.678
02/15/1963	6.691	10.362
05/15/1963	6.773	9.620
08/15/1963	6.689	9.347
11/15/1963	5.977	9.466
02/15/1964	5.770	8.302
05/15/1964	4.728	6.858
08/15/1964	4.482	6.764
11/15/1964	3.805	6.006
02/15/1965	3.491	5.184
05/15/1965	3.527	5.563
08/15/1965	3.457	5.055
11/15/1965	4.378	6.502
02/15/1966	5.253	7.678
05/15/1966	6.691	10.362
08/15/1966	8.922	13.998
11/15/1966	11.218	16.663
02/15/1967	13.470	19.952
05/15/1967	15.374	23.543
08/15/1967	17.644	26.857
11/15/1967	18.129	26.767
02/15/1968	17.811	28.334
05/15/1968	15.208	23.287
08/15/1968	15.288	23.190
11/15/1968	13.341	19.881

Effective bioassay date	GM (50th) nCi	GM*GSD (84th) nCi
02/15/1969	11.964	18.931
05/15/1969	10.544	16.593
08/15/1969	8.526	13.837
11/15/1969	8.198	13.210
02/15/1970	6.417	12.039
05/15/1970	5.877	9.856
08/15/1970	5.417	9.242
11/15/1970	4.770	8.025
02/15/1971	4.049	7.580
05/15/1971	3.195	6.012
08/15/1971	2.574	4.939
11/15/1971	2.667	5.467
02/15/1972	2.824	5.511
05/15/1972	3.022	5.516
08/15/1972	2.176	4.728
11/15/1972	2.222	4.332
02/15/1973	2.0544	4.5035
05/15/1973	1.8482	3.4682
08/15/1973	1.8296	3.3453
11/15/1973	1.6404	3.3004
02/15/1974	1.2505	3.0204
05/15/1974	0.9186	2.1838
08/15/1974	1.0889	2.4621
11/15/1974	1.1091	2.7017
02/15/1976	1.0488	2.1653
05/15/1976	1.1197	2.6952
08/15/1976	0.9322	2.1818
11/15/1976	1.6176	3.9736
02/15/1977	1.3651	2.9877
05/15/1977	1.4688	3.4256
08/15/1977	1.1219	2.9244
11/15/1977	0.8683	2.2466
02/15/1978	1.0525	2.6430
05/15/1978	0.7876	2.3797
08/15/1978	0.7788	2.2337
11/15/1978	1.0824	2.6808

Effective bioassay date	GM (50th) nCi	GM*GSD (84th) nCi
02/15/1979	1.1775	2.9579
05/15/1979	0.8671	2.0518
08/15/1979	0.9219	2.1979
11/15/1979	1.2393	2.6536
02/15/1980	1.1519	2.8199
05/15/1980	0.8175	2.9124
08/15/1980	0.6695	1.8971
11/15/1980	0.7321	1.9398
02/15/1981	0.8278	2.1018
05/15/1981	0.4992	1.1927
08/15/1981	0.3353	0.9534
11/15/1981	0.4740	1.0964
02/15/1982	0.5655	1.3484
05/15/1982	0.4695	1.2468
08/15/1982	0.4364	1.0269
11/15/1982	0.5316	1.2952
02/15/1983	0.4257	1.1238
05/15/1983	0.3023	0.8154
08/15/1983	0.3705	0.9053
11/15/1983	0.4354	1.1195
02/15/1984	0.2487	0.6537
05/15/1984	0.2461	0.6285
08/15/1984	0.2430	0.6134
11/15/1984	0.2398	0.5927
02/15/1985	0.2450	0.6327
05/15/1985	1.1416	2.7971
08/15/1985	1.1220	2.8167
11/15/1985	1.1235	2.8170
04/01/1986	1.1169	2.7720
10/1/1986	1.1106	2.7455
04/01/1987	0.9186	2.1838
10/01/1987	1.0889	2.4621
04/01/1988	1.1091	2.7017
10/01/1988	1.0488	2.1653

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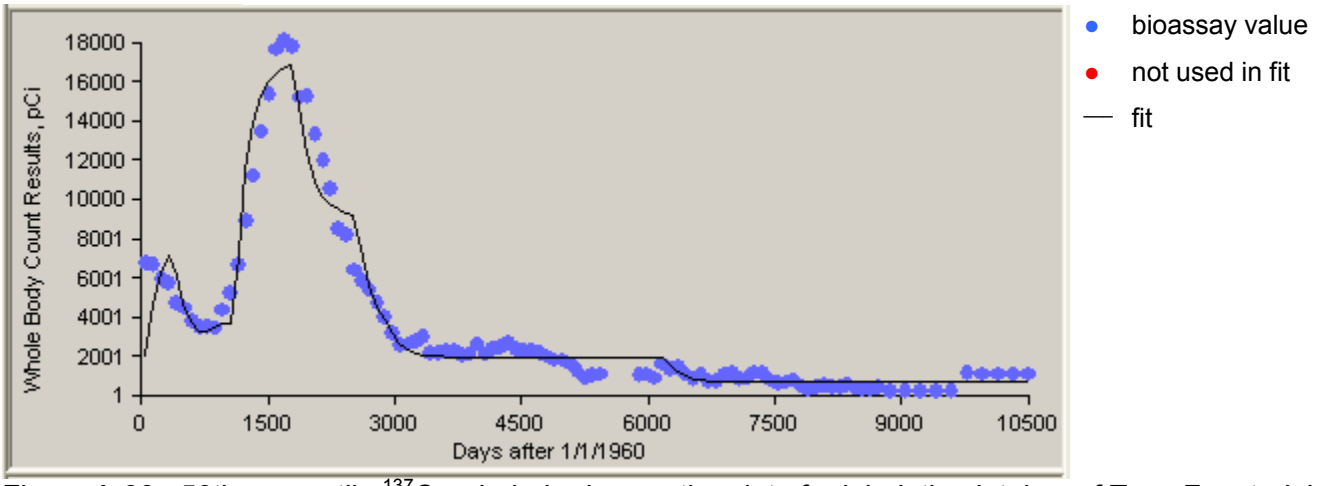

Figure A-33. 50th-percentile ^{137}Cs whole-body counting data for inhalation intakes of Type F material, 1960 to 1988.