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**Monitoring Feasibility Evaluation for Exotic Radionuclides Produced by the Oak Ridge National Laboratory Isotopes Division**

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## PUBLICATION RECORD

| EFFECTIVE DATE | REVISION NUMBER | DESCRIPTION |
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| 03/29/2018 | 00 | New report evaluating the Oak Ridge National Laboratory capability to monitor internal exposure to exotic radionuclides that were produced by the laboratory's Isotopes Division. Incorporates formal internal and NIOSH review comments. Initiated by Joseph S. Guido. |
| 03/10/2023 | 01 | Document revised to address comments received following SC&A review as well as during Working Group discussions. Specific changes include clarifying the document's scope and intent as being an evaluation of ORNL monitoring capabilities regarding work by Isotope Group employees or within Isotope Group facilities. Accordingly, Appendix C ("Dose Reconstruction Approach for Iodine") was removed and will be included in a separate document. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training is not required. Initiated by Pat McCloskey and authored by Joseph S. Guido. |

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| Ci | curie |
| cm | centimeter |
| cpm | counts per minute |
| d | day |
| DAC | derived air concentration |
| DOE | U.S. Department of Energy |
| HP | health physics |
| hr | hour |
| ICRP | International Commission on Radiological Protection |
| in. | inch |
| keV | kiloelectron-volt (1,000 electron-volts) |
| m | meter |
| mCi | millicurie |
| min | minute |
| mL | milliliter |
| MPC | maximum permissible concentration |
| mrem | millirem |
| NBS | National Bureau of Standards |
| NIOSH | National Institute for Occupational Safety and Health |
| NOCTS | NIOSH-Division of Compensation Analysis and Support Claims Tracking System |
| ORAU | Oak Ridge Associated Universities |
| ORAUT | ORAU Team |
| ORNL | Oak Ridge National Laboratory |
| SEC | Special Exposure Cohort |
| SRDB Ref ID | Site Research Database Reference Identification (number) |
| WBC | whole body count |
| yr | year |
| Y-12 | Y-12 Plant |
| µCi | microcurie |

## 1.0 PURPOSE

This report evaluates the Oak Ridge National Laboratory (ORNL) capabilities for internal monitoring of radionuclides produced by the Isotopes Division and its predecessors from 1955 to 1988. This evaluation was initiated after the publication of the Special Exposure Cohort (SEC) evaluation report for ORNL (SEC-00189) [NIOSH 2012]. As a result of the SEC-00189 ER, a class was added to the SEC from the beginning of ORNL operations (June 17, 1943) through July 31, 1955. The SEC addressed isotopes of uranium, plutonium, thorium, and mixed fission products but did not evaluate the dose reconstruction feasibility for radionuclides produced by the isotopes group. Because the class recommended in the SEC-00189 evaluation report covered the entire period petitioned, NIOSH closed the SEC-189 petition evaluation.

Throughout this document the term *exotic* refers to radionuclides produced by the isotopes group to generally delineate these radionuclides from those more globally handled at the facility (e.g., uranium, plutonium and mixed fission and activation products). Because of the potential challenges involved in monitoring intakes from such a wide variety of materials, NIOSH requested this evaluation; its purpose is to identify any areas where dose reconstruction might be infeasible. The evaluation methodology entailed the following steps:

- Identifying radionuclides produced by the Isotopes Division,
- Identifying available ORNL Health Physics (HP) program bioassay methodologies,
- Chronological benchmarking of the available bioassay methods against the radionuclide inventory to identify potential gaps in monitoring capability, and
- Identify areas where bioassay monitoring gaps exist.

## 2.0 SCOPE

The period under evaluation in this report is August 1, 1955, through December 31, 1988. The start date was selected to coincide with the end of the SEC period [NIOSH 2012]. The end date coincides with the end of large-scale isotope production at ORNL. All operations under evaluation were managed by ORNL. Although most of the facilities were on the ORNL campus (many in an area termed “Isotope Circle”), the Isotope Division also used the cyclotron and calutron facilities at the Y-12 Plant. This report evaluates the capability of the ORNL HP program to monitor all materials that were produced and handled by the Isotopes Division, regardless of production location, in order to determine if bioassay technology deficiencies existed that could result in improper monitoring. The scope of this report is limited to isotope production activities; it excludes treatment of decontamination and decommissioning, site-wide construction, and maintenance activities that may encompass these same facilities. Although this report identifies potential dose reconstruction challenges, it is not an evaluation of whether a co-exposure model approach could be developed for every radionuclide.

## 3.0 ISOTOPE PRODUCTION

Isotope production occurred at both ORNL and Y-12 under ORNL management. At times, Y-12 workers supported efforts at the facilities and, in some cases, Y-12 employees were administratively transferred to ORNL. Note that the facilities listed in this report are the primary facilities used by the isotopes group and are presented for a historical perspective. The inventory listing was developed independent of the facility list but instead was related to isotope group activities across the site.

## 3.1 ORNL FACILITIES

In the late 1940s, ORNL initiated a program to replace the wartime temporary structures with more permanent buildings. A major focus of this program was the provision for a radioisotope complex of 10 buildings designed for processing, packaging, and shipping radioisotopes [Carver and Slater 1994].

Isotopes are produced in reactors; extracted by chemical processes; and then used for biological, medical, and industrial research. As early as 1946, radioisotopes were produced in the Oak Ridge Research Reactor. In 1947, the Isotopes Section (later Division) was formed at the Clinton Laboratories. By 1950, ORNL was distributing (by order) over 50 radioisotopes to research centers around the world.

Figure 3-1 shows the radioisotope buildings constructed under this expansion, which are grouped in an area termed “Isotope Circle.” The ten buildings, one stack, and their original designations were:

- 3028 Radioisotope Processing Building F,
- 3029 Radioisotope Processing Building E,
- 3030 Radioisotope Processing Building D,
- 3031 Radioisotope Processing Building C,
- 3032 Radioisotope Processing Building B,
- 3033 Radioisotope Processing Building A,
- 3034 Radioisotope Service Building,
- 3036 Decontamination Building,
- 3037 Radioisotope Area Office Building,
- 3038 Radioisotope Analytical and Pack Building, and
- 3039 Exhaust Stack.

One building (3038) was used for the analysis, storage, packaging, and shipment of materials. Six small buildings (3028 to 3033) were dedicated to radioisotope production and development, each having dedicated shielding and remote-handling capabilities. The use of dedicated small areas for material processing was purposeful to minimize interaction between different processing areas and to minimize the potential number of exposed individuals within each operational area [Thompson 1952].

The Fission Products Development Laboratory (Building 3517) was completed in 1958. It was originally designed and built to separate kilocurie quantities of $^{137}$Cs, $^{90}$Sr, $^{144}$Ce, and $^{147}$Pm from liquid reduction-oxidation and plutonium-uranium extraction waste streams. The facility was modified in 1963 to allow production of megacurie amounts of $^{137}$Cs, $^{90}$Sr, and $^{144}$Ce, primarily for use in the Systems for the Nuclear Auxiliary Power program [Martin Marietta Energy Systems (MMES) 1986].

In 1962, Building 3047 was built to house the Radioisotopes Development Laboratory for research and development and to produce radioisotopes. The radioactive materials the Isotopes Division handled included $^{90}$Sr, $^{137}$Cs, $^{152}$Eu, $^{154}$Eu, $^{238}$Pu, $^{111m}$Sn, $^{166}$Dy/Ho, $^{186}$Re, and $^{188}$W/$^{188}$Re. A single sealed source of $^{90}$Sr had activity as high as 350,000 Ci [MMES 1995].

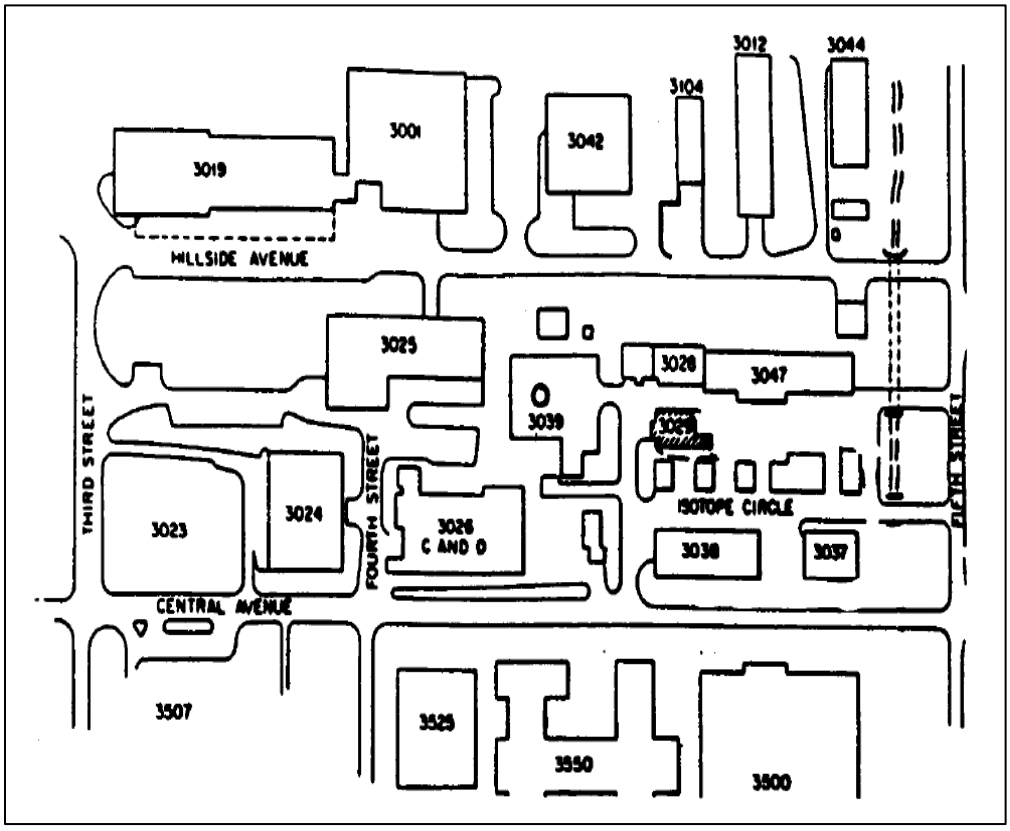


Figure 3-1. General layout of isotope facilities [Carver and Slater 1994].

## 3.2 Y-12 FACILITIES

Concurrently with production of isotopes in reactors on the ORNL campus, the Isotopes Division involved the use of the cyclotron and calutron facilities on the Y-12 site to produce isotopes.

The calutron (electromagnetic separation) facilities were originally built to separate uranium isotopes and recover uranium enriched in $^{235}U$. With the successful operation of the gaseous diffusion process, the calutrons were phased out as a production operation for enriching uranium.

By the end of 1950, plans were made to use the calutron facilities to separate the isotopes of plutonium to allow more accurate measurement of their nuclear properties. The first isotope to be separated was to be $^{240}Pu$, followed by $^{242}Pu$ and $^{244}Pu$. Before 1962, radioisotope production in the Y-12 facility was limited to small quantities of plutonium and uranium that were produced in one or two calutrons in Track 5 of Building 9204-3, which was functionally separated from the other calutrons. In 1962, a containment facility was built in Building 9204-3 that included separations areas, chemical processing areas, a change room, and a locker room. The actinide area operated continuously from 1962 to 1972 and chiefly separated isotopes of plutonium and uranium but included many other isotopes:

- Americium-241, -242, -243;
- Beryllium-9, -10;
- Calcium-40, -41, -42, -43, -44, -46, -48;
- Curium-243, -244, -245, -246, -247, -248, -250;

- Lead-201, -204, -205, -206, -207, -208;
- Plutonium-238, -239, -240, -241, -242, -244;
- Promethium-146, -147;
- Samarium-147, -148, -149, -150, -151, -152, -154;
- Thorium-228, -230, -232; and
- Uranium-232, -233, -234, -235, -236, -238.

### 3.3 MATERIAL TRANSFERS

Figure 3-2 shows the production flow between ORNL, Y-12, and offsite locations. Certain radionuclides were produced at the ORNL Graphite Reactor, the cyclotron, and the calutrons. Some materials containing exotic radionuclides were shipped off site right after production, while others underwent further processing at ORNL first.

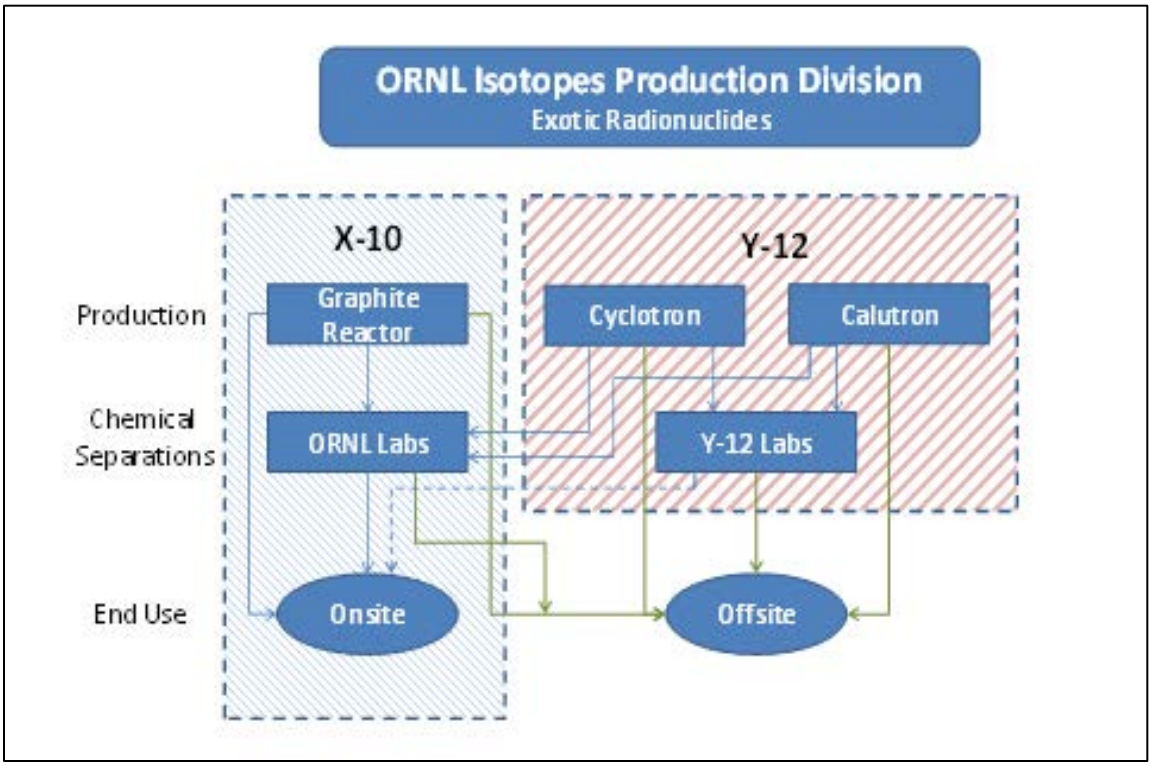


Figure 3-2. Isotope production flow, 1955 to 1965 [NIOSH 2012].

## 4.0 EVALUATION OF BIOASSAY PROGRAM AND DATA

### 4.1 SAMPLING PROGRAM

ORNL has collected urine and fecal samples from individuals suspected of potential intakes from 1945 (and possibly as early as 1943) to the present. The processing of urine samples at the ORNL Urinalysis Building started in 1947 [Davis and Warden 1954] and was performed by the ORNL Body Fluids Analysis group [Burnett 1948].

Urine samples were collected based on the Area Health Physicist's knowledge of field conditions (e.g., known spills or incidents, air and contamination sample results). A June 1950 document, *Procedure for the Collection of Urine Samples*, indicates that it was ORNL policy to "collect and analyze certain body fluids of all employees who work with large quantities of uranium, plutonium, and other types of radioactive materials" [Hart 1950]. This procedure gave the responsibility for the selection of individuals for urine bioassay to the area HP staff. Urine samples were to be submitted along with a request form (Form X-386) indicating, among other things, the type and quantity of radioactivity with which the individual worked. A March 1954 revision to this procedure included consideration of the need to make a second request for sample submission and made use of the same request format [Warden 1954]. By 1957, the sampling request was revised to include a list of routine analytes that could be requested (H-3, polonium, plutonium, radium, strontium, uranium, gross alpha, and gross beta) along with a space to write in a radionuclide name.

In earlier years, the element of concern was extracted chemically from the biological sample and the total radioactivity of the element in the extract was measured. At some point after the extraction and sample count, the total sample activity was attributed to a specific radionuclide. Many of the isotopic assignments were based on process knowledge because isotope-specific analyses were not possible or routinely performed.

To evaluate the effectiveness of its bioassay program, and as a possible basis for improvement, ORNL conducted a study of all urinalysis samples from July 2, 1953, to August 23, 1954 [Davis and Warden 1954]. The total number of samples was 1,265. ORNL concluded that the method for that period seemed adequate. They recommended that a major emphasis be placed on obtaining samples for employees regularly working with radioactive materials and that the sampling schedule be left at the discretion of the HP area surveyor. It was further recommended that the surveyor annually select at random a number of employees who do not work regularly with radioactive materials and suggest to them that they submit a sample.

Infrequently, a request was made for determination of a radionuclide not included in the routine procedure. Such determinations were usually made by the use of, or modification of, existing analytical methods from the literature [Henley 1968].

Attachment A summarizes the initial development of ORNL bioassay methods. The discussion in this attachment provides detail up through the initial deployment of each bioassay method.

## 4.2 ORNL BIOASSAY DATA

The Oak Ridge Associated Universities Team (ORAUT) obtained a copy of the ORNL bioassay database dated April 28, 2013 [UT-Battelle 2013]. This database contains the results of 104,957 individual bioassay samples from September 7, 1949, through December 21, 1988. Of these, there are 94,988 with collection dates during the period under evaluation in this report. These 94,988 samples (3,121 fecal; 91,867 urine) were collected from 7,564 individual workers and subjected to analysis for 62 different individually identified analytes and code 000, which indicates other. This code indicates a nonstandard analytical method. There were 1,532 code 000 urine samples from 502 individuals, 52 code "OO0" urine samples from 33 individuals, and 140 code "OF0" fecal samples for 64 individuals (note that the combination of capital "O" and numeral "0" in a code is not a transcription error.) Tables 4-1 and 4-2 provide a summary of the bioassay methods the ORNL bioassay database lists for urine and fecal samples, respectively.

Table 4-1. Urine bioassay codes used at ORNL, 1955 to 1988.

| Bioassay code | Description/analyte | Number of samples | Period in use |
|---|---|---|---|
| 000 | Other | 1,532 | 1955,1958,1961,1963–1974,1976–1977,1979–1983,1985 |
| OO0[a] | Other | 52 | 1986–1988 |
| 001 | S-35 | 3 | 1958–1959,1961 |
| 002 | Co-60 | 14 | 1961–1963 |
| 003 | Pb-210 | 3 | 1960 |
| 004 | Na-24 | 2 | 1960 |
| 005 | Zr-95/Nb-95 | 13 | 1960–1963 |
| 006 | Tc-99 | 11 | 1960–1964 |
| 007 | As-74 | 6 | 1960 |
| 008 | Br-82/Br-83 | 6 | 1960–1961 |
| 009 | Fe-59 | 11 | 1960,1964 |
| 010 | Mn-54 | 3 | 1960,1978 |
| 011 | I-131 | 13 | 1958,1961–1964 |
| 012 | Cs-132 | 2 | 1961 |
| 013 | Gross beta | 153 | 1955,1960–1964 |
| 014 | Ba-140 | 1 | 1961 |
| 015 | Sb-125 | 18 | 1962–1963 |
| 016 | Tl-204 | 7 | 1962 |
| 017 | Np-237 | 12 | 1962–1964 |
| 018 | Ag-110m | 1 | 1963 |
| AM0 | Am-241 | 1 | 1987 |
| C-14 | C-14 | 67 | 1986–1988 |
| CM0 | Cm-244 | 11 | 1986,1988 |
| CO0 | Co-60 | 144 | 1963,1965,1967–1969,1972–1976,1982,1984,1987–1988 |
| CS0 | Cesium beta | 1,589 | 1964–1970,1972–1977,1980–1988 |
| CS7 | Cs-137 | 284 | 1955–1957,1959–1964 |
| FP0 | Fission products | 17 | 1956–1958 |
| FU0 | Total rare earth | 1,333 | 1959–1967,1969–1978,1980,1985 |
| GA0 | Gross alpha | 132 | 1965–1973,1975,1979–1980 |
| GB0 | Gross beta | 26 | 1961,1965–1966,1968–1971,1973,1984 |
| GD0 | Gd-153 | 40 | 1987–1988 |
| GG0 | Gross gamma | 9 | 1972,1984,1986–1988 |
| GU0 | Gross alpha | 12,759 | 1955–1964 |
| HY3 | H-3 | 5,680 | 1955–1988 |
| I25 | I-125 | 8 | 1987–1988 |
| I31 | I-131 | 25 | 1987–1988 |
| NP0 | Np-237 | 64 | 1965–1970,1972,1978–1979 |
| PA0 | Pa-231 | 12 | 1968–1973,1975,1977 |
| PA3 | Pa-233 | 155 | 1955–1958,1960–1961,1964–1966,1969–1971,1975 |
| PH2 | P-32 | 232 | 1957–1965,1968–1969,1973–1976,1978–1984 |
| PM7 | Pm-147 | 5 | 1987 |
| PO0[a] | Po-210 | 48 | 1955–1957,1960–1961,1963,1966–1967,1975,1979 |
| PU0 | Pu-239 | 15,016 | 1964–1988 |
| PU1 | Pu-241 | 147 | 1968–1974,1976–1979,1981–1985 |
| PU9 | Pu-239 | 1,738 | 1957–1958,1960–1964 |
| RA0 | Ra-226 | 329 | 1955–1961,1963,1966,1968,1976–1977 |
| RA6 | Ra-226 | 1 | 1987 |
| RU6 | Ru-106 | 81 | 1958,1960,1962–1967,1972,1985 |
| SR0 | Sr-90 | 26,408 | 1955–1988 |
| SR5 | Sr-85 | 11 | 1960,1987 |
| SR9 | Sr-89 | 368 | 1960–1962,1966,1969 |

Table 4-1. Urine bioassay codes used at ORNL, 1955 to 1988 (continued).

| Bioassay code | Description/analyte | Number of samples | Period in use |
|---|---|---|---|
| TA0 | Ta-180 | 2 | 1986 |
| TP0 | Trans plutonium alpha | 8,162 | 1958,1964,1966–1988 |
| URO | Uranium | 15,100 | 1955–1988 |
| **All codes** | **Total** | **91,867** | 1955–1988 |

a. The combination of capital "O" and numeral "0" in a code type is not a transcription error.

Table 4-2. Fecal bioassay codes in use at ORNL, 1955 to 1988.

| Bioassay code | Description/analyte | Number of samples | Period in use |
|---|---|---|---|
| OF0[a] | Other | 140 | 1964–1970,1976,1983,1988 |
| GF0 | Gross alpha | 2,195 | 1955–1968,1972,1975 |
| PF0 | Pu-239 | 109 | 1968–1973,1975–1983 |
| PF3 | Pa-233 | 79 | 1957–1958,1961 |
| RF0 | Rare earth | 70 | 1955,1960,1963–1965,1971–1972 |
| SF0 | Sr-90 | 243 | 1957–1958,1960–1974,1980 |
| SF9 | Sr-89 | 42 | 1960 |
| TF0 | Trans plutonium | 178 | 1968–1983,1986 |
| UF0 | Uranium | 65 | 1956,1963–1965,1968–1969,1973–1976,1979–1980 |
| **All codes** | **Total** | **3,121** | 1955–1988 |

a. The combination of capital "O" and numeral "0" in a code type is not a transcription error.

To assess the target radionuclide associated with the 1532 code 000 bioassay samples, the ORAU Team examined both the data already on file for 114 workers in the NIOSH-Division of Compensation Analysis and Support Claims Tracking System (NOCTS) as well as the bioassay cards for 388 individuals that are not in that system. The Team reviewed the bioassay card data to identify the analyte and compile the bioassay information into a data file. A total of 1,584 individual urine bioassay samples were identified for 492 individuals.[1] These samples were analyzed for 53 different analytes. Table 4-3 provides a summary of the reported analytes for these code 000 samples. Note that the bioassay cards for the 140 code OF0 (fecal) and 52 code OO0 (urine) samples were not requested.

Table 4-3. Bioassay code 000 with monitored nuclide, 1955 to 1988.

| Bioassay code | Description/analyte | Number of samples | Period in use |
|---|---|---|---|
| 000 | Am | 60 | 1965–1967 |
| 000 | Am-241 | 21 | 1965–1967 |
| 000 | Am-243 | 2 | 1968 |
| 000 | Bk-249 | 7 | 1965, 1969 |
| 000 | C-14 | 14 | 1968, 1970–1973, 1979, 1982 |
| 000 | Ca-45 | 19 | 1965–1966, 1968 |
| 000 | Cd-109 | 1 | 1973 |
| 000 | Ce | 1 | 1969 |
| 000 | Cl-36 | 3 | 1968 |
| 000 | Cm | 469 | 1965–1967 |
| 000 | Cm-242 | 53 | 1965–1967 |
| 000 | Cm-244 | 17 | 1965–1967 |
| 000 | Co-57 | 2 | 1965 |
| 000 | Co-60 | 4 | 1961, 1963, 1983 |

[1] The ORNL bioassay database is known to be incomplete (some samples were not entered into the database). Therefore, it is expected that the number of database samples and the number of samples from the bioassay cards for individuals identified in the database might not be equal.

Table 4-3. Bioassay code 000 with monitored nuclide, 1955 to 1988 (continued).

| Bioassay code | Description/analyte | Number of samples | Period in use |
|---|---|---|---|
| 000 | Cr | 2 | 1964 |
| 000 | Cr-51 | 4 | 1964, 1968, 1976 |
| 000 | Cs-132 | 1 | 1961 |
| 000 | Eu-152 | 2 | 1985 |
| 000 | Eu-154[a] | 1 | 1988 |
| 000 | Eu-155[a] | 1 | 1988 |
| 000 | Fe-55 | 5 | 1983 |
| 000 | Fe-59 | 2 | 1964–1965 |
| 000 | Ga-66/67 | 5 | 1970 |
| 000 | Ga-67 | 3 | 1968, 1971 |
| 000 | Gd-153 | 1 | 1987 |
| 000 | I | 64 | 1963, 1965–1973, 1976 |
| 000 | I-125 | 1 | 1976 |
| 000 | I-131 | 51 | 1958, 1965–1967, 1969–1971, 1973–1974 |
| 000 | Ir-192 | 2 | 1981 |
| 000 | Nb-95 | 2 | 1968–1969 |
| 000 | P-32 | 2 | 1968 |
| 000 | Pa | 1 | 1965 |
| 000 | Pm | 3 | 1965–1966 |
| 000 | Pm-147 | 2 | 1967 |
| 000 | Pu-241 | 74 | 1967 |
| 000 | Ru | 29 | 1968–1969, 1971 |
| 000 | Ru-103 | 2 | 1965 |
| 000 | Ru-103/106 | 4 | 1969 |
| 000 | Ru-106 | 9 | 1968–1969, 1971–1972 |
| 000 | S-35 | 5 | 1955, 1968 |
| 000 | Tc | 12 | 1965, 1979–1980 |
| 000 | Tc-99 | 9 | 1976–1977, 1979, 1981, 1983 |
| 000 | Th | 2 | 1965 |
| 000 | Tl-201 | 1 | 1981 |
| 000 | Tm-170 | 1 | 1968 |
| 000 | TrPu | 575 | 1961–1962, 1964–1969, 1974 |
| 000 | W | 1 | 1966 |
| 000 | Y-88 | 2 | 1961 |
| 000 | Y-90 | 1 | 1982 |
| 000 | Zn-65 | 1 | 1968 |
| 000 | Zr | 20 | 1959, 1963, 1967–1969 |
| 000 | Zr-95 | 2 | 1966, 1969 |
| 000 | ZrNb | 17 | 1964, 1968–1969 |
| **All codes** | **Total** | **1,584** | 1955–1988 |

a. Analytical results associated with mixed nuclide release, not an individual nuclide.

## 4.3 NOCTS BIOASSAY DATA

Bioassay data for 1,003 workers in NOCTS were compiled into a spreadsheet. These 1,003 individuals represent the total pool of ORNL workers in NOCTS with bioassay data when the ORAU Team data transcription project was initiated in mid-2014. Although the purpose of this transcription project was to compile a dataset for potential use as a source of ORNL coworker data, the data were used in this report evaluation to ascertain the degree to which the ORNL bioassay database represents the analysis types that were used for individual workers from August 1, 1955, through December 31, 1988. This was done by comparing the data in the NOCTS claim files (i.e., from individual bioassay cards) with the data in the ORNL database for the same individuals. This comparison was made for analytes containing more than 10 samples.

With the exception of gross beta analysis (results of which seem to be missing from the ORNL database between 1955 and 1959), the sample frequency in the ORNL and NOCTS datasets are comparable, although the NOCTS data files tend to be more complete. Tables 4-4 and 4-5 show the results of this evaluation by sample year and by analytical method code, respectively.

Table 4-4. NOCTS versus ORNL database comparison of sample frequency by year (for analytical methods with >10 samples).

| Year | NOCTS sample count | ORNL database sample count | N/O[a] |
|---|---|---|---|
| 1955 | 485 | 467 | 1.04 |
| 1956 | 448 | 415 | 1.08 |
| 1957 | 562 | 517 | 1.09 |
| 1958 | 905 | 863 | 1.05 |
| 1959 | 674 | 615 | 1.10 |
| 1960 | 900 | 875 | 1.03 |
| 1961 | 1,010 | 864 | 1.17 |
| 1962 | 1,232 | 1,046 | 1.18 |
| 1963 | 1,330 | 1,157 | 1.15 |
| 1964 | 1,119 | 998 | 1.12 |
| 1965 | 1,170 | 982 | 1.19 |
| 1966 | 1,057 | 909 | 1.16 |
| 1967 | 878 | 760 | 1.16 |
| 1968 | 805 | 659 | 1.22 |
| 1969 | 870 | 733 | 1.19 |
| 1970 | 702 | 572 | 1.23 |
| 1971 | 687 | 533 | 1.29 |
| 1972 | 530 | 470 | 1.13 |
| 1973 | 701 | 578 | 1.21 |
| 1974 | 515 | 429 | 1.20 |
| 1975 | 360 | 342 | 1.05 |
| 1976 | 433 | 397 | 1.09 |
| 1977 | 311 | 297 | 1.05 |
| 1978 | 324 | 312 | 1.04 |
| 1979 | 271 | 267 | 1.01 |
| 1980 | 265 | 259 | 1.02 |
| 1981 | 194 | 194 | 1.00 |
| 1982 | 330 | 323 | 1.02 |
| 1983 | 254 | 245 | 1.04 |
| 1984 | 254 | 249 | 1.02 |
| 1985 | 213 | 209 | 1.02 |
| 1986 | 225 | 217 | 1.04 |
| 1987 | 172 | 168 | 1.02 |
| 1988 | 188 | 186 | 1.01 |
| **Overall** | **20,374** | **18,107** | **1.13** |

a. N/O = NOCTS Sample Count / ORNL Sample Count-Analytical Methods with >10 total samples (000, CS0, CS7, FU0, GA0, GF0, GU0, HY3, PA3, PF0, PH2, PU, PU0, PU1, PU9, RA0, RF0, SF0, SR9, TF0, TP0, UF0, UR0).

Table 4-5. NOCTS versus ORNL database comparison of sample frequency by analyte code (for analytical methods with >10 samples).

| Analyte code | NOCTS sample count | ORNL database sample count | N/O[a] |
|---|---|---|---|
| 000 | 362 | 298 | 1.21 |
| CS0 | 432 | 367 | 1.18 |
| CS7 | 56 | 49 | 1.14 |
| FU0 | 297 | 273 | 1.09 |
| GA0, GU0, Pu, PU0, PU9 | 6,558 | 5,777 | 1.14 |
| GF0 | 581 | 543 | 1.07 |
| HY3 | 836 | 809 | 1.03 |
| PA3 | 17 | 12 | 1.42 |
| PF0 | 35 | 26 | 1.35 |
| PH2 | 31 | 28 | 1.11 |
| PU1 | 22 | 20 | 1.10 |
| RA0 | 72 | 64 | 1.13 |
| RF0 | 15 | 13 | 1.15 |
| RU6 | 45 | 27 | 1.67 |
| SF0 | 41 | 38 | 1.08 |
| SR0 | 5,761 | 5,091 | 1.13 |
| SR9 | 66 | 66 | 1.00 |
| TF0 | 34 | 27 | 1.26 |
| TP0 | 1,904 | 1,691 | 1.13 |
| UF0 | 20 | 17 | 1.18 |
| UR0 | 3,189 | 2,871 | 1.11 |
| **Overall** | **20,374** | **18,107** | **1.13** |

a. N/O = NOCTS Sample Count/ORNL Sample Count-Analytical Methods with >10 total samples ('000', CS0, CS7, FU0, GA0, GF0, GU0, HY3, PA3, PF0, PH2, PU, PU0, PU1, PU9, RA0, RF0, SF0, SR9, TF0, TP0, UF0, UR0).

To summarize, the ratio of the number of samples for the same group of individuals in NOCTS to that in the ORNL Database is 1.13:1.00. The ratio ranges from 1:1 to 1:1.29 when grouped by year (Table 4-4), and from 1:1 to 1:1.67 when grouped by method (Table 4-5). Note that the higher variance when grouped by analytical method is likely due to the smaller sample set for some of the groups (in comparison with the sets grouped by year). The results are consistent with the conclusion of the ORNL Internal Dosimetry staff that the database is incomplete and might be missing up to 25% of the bioassay samples [ORAUT 2013], albeit comparison between NOCTS and the ORNL database indicate a slightly lower value. Note that this evaluation is only qualitative.

As indicated above, the ORNL database does not contain gross beta results (analyte codes 013 and GB0) between 1955 and 1959. Table 4-6 shows the number of gross beta samples for the same group of individuals when viewed in the NOCTS dataset versus the ORNL database.

Table 4-6. Gross beta samples in NOCTS and ORNL datasets (analyte codes 013 and GB0).

| Dataset | 1955 | 1956 | 1957 | 1958 | 1959 |
|---|---|---|---|---|---|
| NOCTS | 1 | 5 | 26 | 28 | 7 |
| ORNL | 0 | 0 | 0 | 0 | 0 |

This analysis indicates a discrepancy in the presence of gross beta samples (Analyte 013 and GB0) in the ORNL dataset. A review of the underlying data indicates that it was not uncommon for the gross beta analysis to be performed in conjunction with either fission product analysis (FP0), rare earth

analysis (FU0), or strontium analysis (SR0). The results of these accompanying FP0, FU0, or SR0 analyses are in the ORNL database, but the gross beta results are not. It appears that gross beta sample results were not recorded in the ORNL database between 1955 and 1959. However, it is not clear from the data results if the FP0, FU0, or SR0 analyses were initiated as a result of the gross beta analysis result.

## 5.0 EVALUATION OF IN VIVO MONITORING COUNTING PROGRAM

The main whole body count (WBC) room (a shielded vault) was erected in Building 2008 on July 24, 1959, with a 14-in.-thick pre-World War II steel shield. The first recorded background count was made on July 13, 1959, before the door and the roof were completed. The count room was initially used primarily for counting biological samples, such as milk, grass, and cow thyroids [Watts et al. 1995].

Use of the WBC facility for personnel monitoring began in June 1960. The system was configured with a 200-channel tube-type analyzer connected to a single 4- by 4-in. NaI(Tl) crystal. This configuration was initially used to measure 19 individuals involved in known contamination events. From June 1960 to July 1961, the effort was expanded to include an additional 208 persons. The system was then upgraded to a 512-channel analyzer connected to two 8-in.-diameter by 4-in. NaI(Tl) detectors [Morgan 1961].

During the second year of operations (1961 to 1962), improvements in data analysis were instituted that used computer software and additional data handling (i.e., inclusion of paper tape recording). Counter use was again focused on known or suspected internal exposures and resulted in 142 measurements of 102 additional individuals [Morgan 1962]. Starting in 1963, the scope of the counting program was expanded to include routine counting of potentially exposed persons as well as baseline counts on individuals before entry into areas with potential for internal exposure. System capacity was reported at 110 persons per month; and 492 individuals were counted between 1962 and 1963.

By 1964, continued improvements in instrumentation, scheduling, and operations made it possible to further increase system throughput. Between 1963 and 1964, a total of 1,568 counts were performed on 1,370 individuals. Emphasis was placed on routine counting of persons, who were suspected of having experienced an exposure or having a potential for exposure, and on obtaining baseline counts. The 1964 HP Division annual report indicated that “the increased rate of individual counting made it possible to expand the base-line counting and obtain counts on essentially all persons with even a remote chance for exposure” [Morgan et al. 1964].

The goal to obtain a baseline count on essentially every person with a potential for future exposure was completed in May 1965 [Morgan et al. 1965]. Beginning in May, the method of selecting individuals was changed to allow selection by Applied HP personnel. A five-part priority system was implemented, as follows:

1. Persons suspected of having sustained an exposure,

2. Persons being recounted as follow-up to initial elevated in vivo counts,

3. Persons who worked directly with radioactive materials,

4. Persons who worked in the areas where radioactive materials are handled, but who did not work directly with the materials, and

5. Newly hired or other persons for baseline counts before beginning work with radioactive materials.

Based on these criteria, individuals who worked directly with radioactive materials were supposed to have been monitored quarterly, and those who worked where radioactive material was present were to have been monitored semiannually. Baseline counts were to be taken for new hires or other persons requiring a baseline count, and a limited number of workers were to be monitored before termination [Morgan et al. 1965].

By the beginning of the 1966 fiscal year (July 1965), the operation of the whole body counter was reported as being used for "the routine monitoring and evaluation of the extent of exposure to gamma-emitting radioisotopes of all Laboratory employees" [Morgan et al. 1966]. The implementation of this routine monitoring effort was reported to be effective beginning in "the next fiscal year" (i.e., July 1967) due to logistical problems with implementation. As stated in the 1966 HP Division annual report, "…the effort required for selection of workers, the frequency of the counts of the workers, preparation of paperwork proved to be greater than anticipated. The new routine counting program is expected to get under way with the beginning of the new fiscal year."

Although the 1967 HP Division annual report indicates that baseline and specified monitoring frequencies continued to be implemented, contemporary ORNL dosimetry staff indicated that a centrally controlled in vivo monitoring program did not exist at ORNL until approximately 1994 when site internal dosimetrists became responsible for identifying personnel for counting [ORAUT 2004]. Before then, Area HP selected individuals for in vivo monitoring based on an understanding of the exposure potential. The Area HP staff was responsible for determining the radioisotopes to which a worker could be exposed as well as the counting frequencies.

Table 5-1 shows the number of in vivo counts taken each calendar year from the ORNL database [UT-Battelle 2013] and the HP Division annual reports from before 1983. (The HP Division reports after 1982 have not been found). The annual report data were assessed to fill in the gaps in the ORNL dataset, which only lists counts starting in 1962.

Table 5-1. Tabulation of in vivo counts from database versus annual reports.

| Year | Number of in vivo counts from ORNL database[a] | Number of in vivo counts from annual reports[b] | Source (annual report) |
|---|---|---|---|
| 1961 | 0 | 329 | Hart 1964, p. 26 |
| 1962 | 71 | 395 | Hart 1963, p. 19 |
| 1963 | 921 | 1,054 | Hart 1964, p. 26 |
| 1964 | 1,555 | 1,644 | UCC 1965, p. 77 |
| 1965 | 1,169 | 1,222 | UCC 1966, pp. 79–80 |
| 1966 | 696 | 740 | UCC 1967, pp. 85–86 |
| 1967 | 966 | 983 | UCC 1968, pp. 83–84 |
| 1968 | 968 | 964 | UCC 1969, pp. 77–78 |
| 1969 | 1,057 | 1,108 | UCC 1970, p.67 |
| 1970 | 518 | 530 | UCC 1971, p. 11 |
| 1971 | 324 | 332 | UCC 1972, p. 11 |
| 1972 | 259 | 272 | UCC 1973, p. 11 |
| 1973 | 325 | 350 | UCC 1974, p. 14 |
| 1974 | 278 | 278 | UCC 1975, p. 17 |
| 1975 | 330 | 331 | UCC 1976, p. 16 |
| 1976 | 255 | 255 | UCC 1977, p. 14 |
| 1977 | 291 | 291 | UCC 1978, p. 14 |
| 1978 | 306 | 305 | UCC 1979, p. 15 |
| 1979 | 402 | 460 | UCC 1980, p. 14 |
| 1980 | 700 | 750 | UCC 1981, p. 15 |
| 1981 | 557 | 590 | UCC 1982, p. 18 |
| 1982 | 556 | 650 | UCC 1983, p. 19 |
| 1983 | 411 | Not available | Not Applicable |

Table 5-1. Tabulation of in vivo counts from database versus annual reports (continued).

| Year | Number of in vivo counts from ORNL database[a] | Number of in vivo counts from annual reports[b] | Source (annual report) |
|---|---|---|---|
| 1984 | 476 | Not available | Not Applicable |
| 1985 | 525 | Not available | Not Applicable |
| 1986 | 682 | Not available | Not Applicable |
| 1987 | 681 | Not available | Not Applicable |
| 1988 | 753 | Not available | Not Applicable |

a. Source data from UT-Battelle [2013].
b. Includes number of wound counts.

## 6.0 INVENTORY DEVELOPMENT

A detailed inventory of the radionuclides the ORNL Isotopes Division produced and processed was developed using source documents in the ORAU Team Site Research Database (SRDB). In addition, the Team used documents it had collected for development of the ORNL and Y-12 site profiles, and during subsequent visits to capture data about radionuclide production activities. The predominant source data for this inventory included isotope shipping and sales reports as well as various operational and technical report series, as shown in Table 6-1. These data sources, as well as other ad hoc (nonseries) reports in the SRDB, were used to develop an initial inventory of radionuclides and quantities. The resultant inventory represents materials produced by the Isotopes group as opposed to a more general inventory of materials present at the site. For example, individual fission product radionuclides contained within unprocessed reactor fuels are not included within the inventory quantities.

The initial radionuclide listing was reviewed to determine if the produced materials were handled in the ORNL processing facilities or (as in the case of many cyclotron materials) shipped directly off site for processing. Materials that were irradiated at ORNL but processed off site were identified as either “special irradiations” or “service irradiations.” Because these materials were not handled in an unsealed form at ORNL or Y-12, they were not included in the isotope inventory. Thirty-six radionuclides were identified in this category and removed from the initial inventory. The exception to this was the case where a target otherwise identified as a service irradiation ruptured. Fifty (50) documents related to target rupture events were identified by a keyword search of the SRDB. Another 49 documents were identified through a review of the ORNL incident listing [UT-Battelle 2012]. In each event of a target rupture, the relevant radionuclide was retained in the radionuclide inventory if initially present. In a small number of cases, the radionuclide that was identified in the target rupture documentation was not contained on the previously identified inventory and was added (Table 6-2). Two radionuclides ($^{123m}$Te and $^{128}$Te) were identified in the inventory development but were removed because they are effectively stable with half-lives of $9.2 \times 10^{16}$ years and $2.4 \times 10^{24}$ years, respectively).

The ORAU Team reviewed a collection of logbooks in the ORNL records repository. These logbooks were selected from a master listing of over 17,000 logbooks. Logbook categories matching those in the table below were selected to narrow the review to 1,867 logbooks. Of these, 15,961 pages from 823 logbooks were selected for data capture. During the course of the data capture, the ORNL radionuclide inventory listing was referenced so that radionuclides in logbook entries that were not listed on the existing inventory could be identified and subsequently added to the radionuclide inventory listing. As a result of this review, 26 additional radionuclides were identified, and one or more additional inventory years were identified for 19 radionuclides (Table 6-3). Table 6-4 provides the final inventory list based on the above-listed data sources.

Table 6-1. Sources of radionuclide production information.

| Report series name | Publication frequency | Start | End | Source |
|---|---|---|---|---|
| Chemical Technology Division Annual Progress Report | Annual | 1957 | 1988 | ORAUT 2022a |
| Electronuclear Research Division Annual Progress Report | Annual | 1957 | 1961 | ORAUT 2022b |
| Isotope Separations Progress Report | Monthly | 1976 | 1978 | ORAUT2022c |
| Isotopes Development Center Progress Report Curium Program | Variable | 1962 | 1964 | ORAUT 2022d |
| Isotopes Development Center Progress Report Fission Products | Variable | 1962 | 1962 | ORAUT 2022e |
| Isotopes Development Center Progress Report Isotopes Separations | Variable | 1962 | 1964 | ORAUT 2022f |
| Isotopes Development Center Progress Report Radioactive Source Development | Variable | 1962 | 1963 | Beauchamp 1963 |
| Isotopes Development Center Progress Report Reactor and Cyclotron Produced Isotopes | Variable | 1963 | 1963 | ORAUT 2022g |
| Isotopes Development Center Progress Report Target Development | Variable | 1962 | 1963 | ORAUT 2022h |
| Isotopes Development Center newsletter | Variable | 1967 | 1967 | Rupp 1968 |
| Isotopes Division Quarterly Report | Quarterly | 1960 | 1961 | ORAUT 2022i |
| Isotopes Division Research and Development Report | Monthly | 1962 | 1962 | ORAUT 2022j |
| List of Radioisotope Customers with Summary of Radioisotope Shipments | Annual | 1964 | 1988 | ORAUT 2022k |
| ORNL Status and Progress Report | Monthly | 1950 | 1967 | ORAUT 2022l |
| Quantity Data on Radioisotopes | Quarterly | 1959 | 1964 | ORAUT 2022m |
| Radioisotope Cost-Price Study | Annual | 1957 | 1974 | ORAUT 2022n |
| Radioisotope Distribution Program Progress Report | Monthly | 1973 | 1980 | ORAUT 2022o |
| Radioisotope Inventory | Monthly | 1956 | 1966 | ORAUT 2022p |
| Radioisotope Production and Process Development Annual Report | Annual | 1954 | 1956 | ORAUT 2022q |
| Radioisotope Program (8000) Progress Report | Monthly | 1969 | 1973 | ORAUT 2022r |
| Review of Radioisotopes Program | Annual | 1964 | 1967 | ORAUT 2022s |
| Stable Isotope and Heavy Element Inventories | Monthly | 1961 | 1969 | ORAUT 2022t |
| Transuranium Processing Plant Semiannual Report of Production, Status, and Plan | Semiannual | 1969 | 1975 | ORAUT 2022u |

Table 6-2. Radionuclides added to inventory due to target rupture events.

| Radionuclide | Year(s) |
|---|---|
| As-71 | 1960 |
| As-72 | 1960 |
| As-74 | 1958, 1960–1961 |
| Mn-52 | 1960 |
| Mn-54 | 1960 |
| Sr-85 | 1961 |
| Y-88 | 1961 |
| Cs-132 | 1962 |

Table 6-3. Information added during logbook review.

| Radionuclide | Information added[a] | Year(s) | Sources |
|---|---|---|---|
| Beryllium-7 | Production year | 1962 | Butler 1962, p. 9 |
| Sodium-22 | Production year | 1964 | Coleman 1964, p. 4 |
| Chlorine-38 | Radionuclide | 1956 | Cain 1956, p. 8 |
| Scandium-46 | Production year | 1973 | Poggenburg 1972, p. 9 |
| Vanadium-48 | Radionuclide | 1962 | Burrell 1962a, p. 17 |
| Manganese-54 | Production year | 1963 | Butler 1962, p. 25 |
| Cobalt-57 | Production year | 1964 | Millspaugh 1964, p. 12 |
| Nickel-66 | Radionuclide | 1968 | Sillyman 1967, p. 52 |
| Copper-64 | Production year | 1976 | Poggenburg 1972, p. 18 |
| Copper-67 | Production year | 1963 | Butler 1962, p. 26 |
| Gallium-68 | Radionuclide | 1971 | Golden 1970, p. 7 |
| Bromine-85 | Radionuclide | 1963 | Burrell 1962b, p. 15 |
| Rubidium-88 | Radionuclide | 1964 | Coleman 1963b, p. 8 |
| Yttrium-86 | Radionuclide | 1964<br>1968 | Millspaugh 1964, p. 19;<br>Butler 1967, p. 55 |
| Zirconium-97 | Radionuclide | 1971 | Guinn 1970, p. 3 |
| Niobium-92 | Radionuclide | 1963 | Hill 1962b, p. 125 |
| Ruthenium-97 | Production year | 1970 | Poggenburg 1969, p. 6 |
| Ruthenium-105 | Radionuclide | 1956 | Warden 1956, p. 9 |
| Indium-114m | Radionuclide | 1975 | Poggenburg 1972, p. 113 |
| Tin-117m | Radionuclide | 1977 | Poggenburg 1976, p. 8 |
| Tellurium-132 | Radionuclide | 1963<br>1968 | Arthur 1962, p. 17;<br>Miller 1967, p. 17 |
| Barium-135m | Production year | 1970 | Poggenburg 1969, p. 24 |
| Praseodymium-144 | Radionuclide | 1962 | Davis 1961, p. 131 |
| Promethium-145 | Radionuclide | 1968 | Sillyman 1967, p. 56 |
| Promethium-148 | Radionuclide | 1970 | Miller 1969, p. 6 |
| Europium-152 | Production years | 1962<br>1968 | Hill 1962a, p. 5; Butler 1962b, p. 7;<br>Butler 1967, p. 40 |
| Gadolinium-148 | Radionuclide | 1970 | Hill 1969, p. 4 |
| Terbium-156 | Production year | 1968 | Butler 1968, p. 3<br>Golden 1966, p. 143 |
| Terbium-158 | Radionuclide | 1970 | Poggenburg 1969, p. 49 |
| Holmium-166 | Radionuclide | 1968 | Butler 1967, p. 45 |
| Erbium-171 | Radionuclide | 1973 | Poggenburg 1972, p. 26 |
| Polonium-210 | Radionuclide | 1962<br>1966 | Davis 1962, p. 5;<br>Wallace 1966, p. 10 |
| Thorium-228 | Radionuclide | 1962 | Butler 1962b, p. 9 |
| Protactinium-231 | Production years | 1961<br>1962 | Burden 1961, p. 6; Burden 1961, p. 16;<br>Butler 1962a, p. 3 |
| Protactinium-233 | Radionuclide | 1963<br>1964<br>1966<br>1969 | Hill 1962b, p. 22; Coleman 1963a, p. 9;<br>Miller 1965, p. 4; Burrell 1967, p. 11 |
| Uranium-232 | Production years | 1961<br>1962<br>1965 | Burden 1961, p. 13; Butler 1962b, p. 4;<br>Keny 1965, p. 5 |
| Neptunium-236 | Radionuclide | 1965 | Walters 1965, p. 44 |
| Neptunium-237 | Production years | 1961<br>1962 | Burden 1961, p. 10; Butler 1962b, p. 3;<br>Butler 1962a, p. 5 |
| Neptunium-238 | Radionuclide | 1965<br>1966 | Clark 1963, p. 11; Coleman 1963c, p. 18 |

Table 6-3. Information added during logbook review (continued).

| Radionuclide | Information added[a] | Year(s) | Sources |
|---|---|---|---|
| Curium-242 | Production years | 1962<br>1964 | Butler 1962b, p. 6; Butler 1962, p. 11;<br>Millspaugh 1963, p. 26 |
| Curium-244 | Production year | 1962 | Davis 1961, p. 151 |
| Berkelium-249 | Production year | 1964 | Moore 1964, p. 3–71 |
| Californium-252 | Production year | 1962 | Butler 1962a, p. 9 |
| Einsteinium-252 | Radionuclide | 1970 | Butler 1969, p. 12 |
| Fermium-257 | Production years | 1969<br>1970 | Guinn 1968, p. 9;<br>Hill 1969, p. 3 |

a. "Production year" indicates additional inventory year for nuclide already on inventory or Radionuclide. "Radionuclide" indicates addition to nuclide not previously identified on inventory.

Table 6-4. Final radionuclide inventory for Isotopes Division.

| Nuclide | Production years |
|---|---|
| Hydrogen-3 | 1955–1957, 1959–1988 |
| Beryllium-7 | 1955, 1957–1959, 1962, 1964, 1969 |
| Carbon-11 | 1975, 1977, 1979–1980 |
| Carbon-14 | 1955–1975, 1980–1983, 1985 |
| Sodium-22 | 1955–1956, 1961–1964 |
| Sodium-24 | 1955–1967 |
| Magnesium-28 | 1966, 1969–1970, 1977, 1983–1984, 1987–1988 |
| Phosphorus-32 | 1955–1967 |
| Phosphorus-33 | 1964–1965, 1967–1987 |
| Sulfur-35 | 1955–1969 |
| Chlorine-36 | 1955–1972 |
| Chlorine-38 | 1956 |
| Argon-37 | 1955–1957, 1959–1971, 1973–1982 |
| Potassium-40 | 1979 |
| Potassium-42 | 1955–1966 |
| Potassium-43 | 1964–1965, 1967, 1971, 1973–1978, 1980–1981, 1983 |
| Calcium-41 | 1977, 1986 |
| Calcium-45 | 1955–1966 |
| Calcium-47 | 1960–1984 |
| Scandium-46 | 1955–1957, 1959–1973 |
| Scandium-49 | 1955, 1965 |
| Titanium-44 | 1956, 1958 |
| Vanadium-48 | 1962 |
| Chromium-51 | 1955–1967, 1975 |
| Manganese-52 | 1960 |
| Manganese-54 | 1955–1957, 1960, 1963–1965 |
| Iron-55 | 1955–1956, 1959–1966, 1980–1986 |
| Iron-59 | 1955–1956, 1958–1967 |
| Cobalt-56 | 1967, 1972, 1977 |
| Cobalt-57 | 1955–1957, 1964, 1972–1976 |
| Cobalt-58 | 1955–1957, 1959–1965 |
| Cobalt-60 | 1955–1988 |
| Nickel-63 | 1955–1957, 1959–1972, 1978, 1980, 1985–1987 |
| Nickel-66 | 1968 |
| Copper-64 | 1955–1969, 1976 |
| Copper-67 | 1963–1964, 1967–1968, 1970–1971, 1973–1976 |
| Zinc-65 | 1955–1957, 1959–1966 |
| Zinc-69m | 1967, 1973–1974 |
| Gallium-67 | 1958–1959, 1969–1978, 1983 |
| Gallium-68 | 1971 |
| Gallium-72 | 1955, 1957, 1960–1970 |

Table 6-4. Final radionuclide inventory for Isotopes Division (continued).

| Nuclide | Production years |
|---|---|
| Arsenic-71 | 1960 |
| Arsenic-76 | 1956–1957, 1959–1967 |
| Arsenic-77 | 1956–1957, 1959–1966 |
| Selenium-75 | 1955–1957, 1959–1966, 1979–1986 |
| Bromine-82 | 1956–1967 |
| Bromine-85 | 1963 |
| Krypton-85 | 1955–1988 |
| Rubidium-83 | 1969 |
| Rubidium-84 | 1964–1965, 1969, 1975 |
| Rubidium-86 | 1955–1957, 1959–1972 |
| Rubidium-88 | 1964 |
| Strontium-82 | 1970 |
| Strontium-85 | 1955, 1957–1967, 1970, 1986 |
| Strontium-87m | 1960, 1964, 1970 |
| Strontium-89 | 1955–1957, 1959–1963, 1965–1987 |
| Strontium-90 | 1955–1988 |
| Yttrium-86 | 1964, 1968 |
| Yttrium-88 | 1957–1958, 1961–1963, 1965, 1974 |
| Yttrium-90 | 1956–1968, 1973, 1987–1988 |
| Yttrium-91 | 1955–1957, 1959–1978 |
| Zirconium-95 | 1955–1986 |
| Zirconium-97 | 1971 |
| Niobium-90 | 1957 |
| Niobium-92 | 1963 |
| Niobium-92m | 1967 |
| Niobium-95 | 1955–1957, 1959–1981, 1983–1985 |
| Molybdenum-93 | 1957, 1962 |
| Molybdenum-99 | 1957, 1959–1971 |
| Technetium-95m | 1957–1958, 1967, 1970 |
| Technetium-99 | 1955–1957, 1959–1970, 1972–1988 |
| Technetium-99m | 1966, 1968, 1970 |
| Ruthenium-97 | 1959–1960, 1962, 1970 |
| Ruthenium-103 | 1955–1957, 1959–1986 |
| Ruthenium-105 | 1956 |
| Ruthenium-106 | 1955–1957, 1959–1988 |
| Rhodium-102 | 1958 |
| Palladium-103 | 1962, 1964 |
| Palladium-109 | 1957, 1959–1971 |
| Silver-110m | 1955–1957, 1959–1966 |
| Silver-111 | 1956–1957, 1959–1970 |
| Cadmium-109 | 1957–1958, 1960–1961, 1963–1966, 1972 |
| Cadmium-115 | 1955–1956, 1960, 1962–1966 |
| Cadmium-115m | 1955–1956, 1960–1966 |
| Indium-111 | 1969–1971, 1973 |
| Indium-114 | 1955–1957, 1959–1977, 1981 |
| Indium-114m | 1975 |
| Tin-113 | 1955–1957, 1959–1967, 1979 |
| Tin-117m | 1977 |
| Tin-119m | 1986 |
| Antimony-122 | 1956, 1959–1968, 1971, 1987 |
| Antimony-124 | 1955–1957, 1959–1967 |
| Antimony-125 | 1955–1957, 1959–1966 |

Table 6-4. Final radionuclide inventory for Isotopes Division (continued).

| Nuclide | Production years |
|---|---|
| Arsenic-74 | 1957–1959, 1961, 1965 |
| Arsenic-72 | 1960 |
| Tellurium-121 | 1957 |
| Tellurium-132 | 1963, 1968 |
| Iodine-123 | 1965, 1967–1970 |
| Iodine-125 | 1957, 1961–1964 |
| Iodine-129 | 1955–1957, 1959–1988 |
| Iodine-130 | 1960–1972, 1985 |
| Iodine-131 | 1955–1976, 1978–1980, 1983, 1985–1986, 1988 |
| Iodine-132 | 1967–1972 |
| Iodine-133 | 1961, 1967–1968, 1977 |
| Xenon-127 | 1983, 1987–1988 |
| Xenon-133 | 1960–1976, 1978–1980 |
| Cesium-131 | 1965 |
| Cesium-132 | 1962 |
| Cesium-134 | 1955–1957, 1959–1966 |
| Cesium-137 | 1955–1988 |
| Barium-131 | 1955–1957, 1959–1971 |
| Barium-133 | 1955–1957, 1959–1972 |
| Barium-135m | 1970, 1986 |
| Barium-140 | 1955–1957, 1959–1968, 1970–1978, 1980–1981, 1983 |
| Lanthanum-140 | 1955–1957, 1959–1966, 1987 |
| Cerium-139 | 1955, 1957–1958 |
| Cerium-141 | 1955–1957, 1959–1966, 1970 |
| Cerium-144 | 1955–1979, 1981–1988 |
| Praseodymium-142 | 1956–1957, 1959–1968, 1970 |
| Praseodymium-143 | 1955–1957;1959–1968, 1970, 1972–1973 |
| Praseodymium-144 | 1962 |
| Neodymium-140 | 1969 |
| Neodymium-147 | 1955–1957, 1959–1973, 1979 |
| Neodymium-149 | 1979 |
| Promethium-145 | 1968 |
| Promethium-146 | 1974 |
| Promethium-147 | 1955–1968, 1970–1987 |
| Promethium-148 | 1970 |
| Samarium-151 | 1968–1982, 1984–1987 |
| Samarium-153 | 1956–1957, 1959–1961, 1963–1969 |
| Europium-152[a] | 1962, 1968, 1974–1975, 1978–1981, 1984–1985, 1988 |
| Europium-155 | 1955–1957, 1959–1968, 1975 |
| Gadolinium-148 | 1970 |
| Gadolinium-153 | 1971, 1973–1988 |
| Terbium-156 | 1958, 1967–1968 |
| Terbium-158 | 1970 |
| Dysprosium-157 | 1975 |
| Dysprosium-159 | 1957, 1961 |
| Dysprosium-166 | 1965, 1984 |
| Holmium-156 | 1965 |
| Holmium-166 | 1968 |
| Erbium-171 | 1973 |
| Thulium-170 | 1962–1971, 1974–1975 |
| Thulium-171 | 1967 |
| Ytterbium-169 | 1980, 1986 |
| Hafnium-181 | 1955, 1957, 1959–1977, 1979–1980 |

Table 6-4. Final radionuclide inventory for Isotopes Division (continued).

| Nuclide | Production years |
|---|---|
| Tantalum-182 | 1955–1957, 1959–1972, 1974 |
| Tungsten-181 | 1957–1958 |
| Tungsten-185 | 1955–1957, 1959–1971 |
| Tungsten-187 | 1955–1957, 1959–1970 |
| Rhenium-186 | 1957, 1959–1972, 1979 |
| Osmium-185 | 1957, 1966 |
| Osmium-191 | 1957, 1959–1970, 1984 |
| Iridium-192 | 1955–1968, 1970–1971, 1973–1988 |
| Iridium-194 | 1959, 1961, 1963, 1968 |
| Platinum-195m | 1972–1974, 1978 |
| Platinum-197 | 1965 |
| Gold-195 | 1961 |
| Gold-198 | 1955, 1957–1966 |
| Gold-199 | 1955, 1957, 1959–1967 |
| Mercury-197 | 1957–1966 |
| Mercury-203 | 1955–1957, 1959–1967 |
| Thallium-201 | 1975 |
| Thallium-204 | 1955–1971 |
| Lead-203 | 1972–1973 |
| Bismuth-206 | 1957–1958 |
| Bismuth-207 | 1957 |
| Bismuth-210 | 1955–1957, 1959–1970 |
| Polonium-210 | 1962, 1966 |
| Thorium-228 | 1962 |
| Thorium-229 | 1968, 1970–1971, 1973–1974, 1977, 1979–1986, 1988 |
| Thorium-230 | 1956, 1962–1963, 1965, 1967–1976, 1978–1988 |
| Thorium-232 | 1963, 1968–1969, 1972–1976, 1978–1987 |
| Thorium-234 | 1981 |
| Protactinium-231 | 1961–1963, 1965–1966, 1968–1969, 1976–1981, 1984–1986 |
| Protactinium-233 | 1963–1964, 1966, 1969 |
| Uranium-232 | 1961–1965, 1968, 1970–1971, 1974–1979 |
| Uranium-233 | 1961–1963, 1965–1988 |
| Uranium-234 | 1956, 1961–1963, 1965–1988 |
| Uranium-235 | 1955–1957, 1961–1963, 1965–1988 |
| Uranium-236 | 1955–1956, 1961–1963, 1965–1988 |
| Uranium-238 | 1955–1956, 1961–1988 |
| Neptunium-236 | 1965 |
| Neptunium-237 | 1955–1957, 1959, 1961–1962, 1964–1965, 1967–1968, 1970, 1972–1987 |
| Neptunium-238 | 1965–1966 |
| Plutonium-236 | 1968, 1970, 1973, 1975, 1981, 1984, 1986 |
| Plutonium-237 | 1984, 1986 |
| Plutonium-238 | 1961–1963, 1965, 1968–1985, 1987–1988 |
| Plutonium-239 | 1955–1956, 1961–1972, 1974–1985, 1987–1988 |
| Plutonium-240 | 1961–1966, 1968–1986, 1988 |
| Plutonium-241 | 1955–1956, 1959, 1962–1975, 1977–1986 |
| Plutonium-242 | 1961–1988 |
| Plutonium-244 | 1968, 1970–1982 |
| Americium-241 | 1959–1988 |
| Americium-243 | 1961–1978, 1980–1986, 1988 |
| Curium-242 | 1962–1966, 1968, 1986 |
| Curium-243 | 1965, 1972–1973, 1975–1976, 1981–1983 |
| Curium-244 | 1962–1964, 1966–1988 |

Table 6-4. Final radionuclide inventory for Isotopes Division (continued).

| Nuclide | Production years |
|---|---|
| Curium-245 | 1969, 1972–1973, 1986 |
| Curium-246 | 1970–1971, 1973, 1977, 1988 |
| Curium-247 | 1969, 1972 |
| Curium-248 | 1968–1980, 1982–1984, 1986, 1988 |
| Berkelium-249 | 1964, 1967, 1969–1984, 1986, 1988 |
| Californium-248 | 1972 |
| Californium-249 | 1968–1976, 1979–1982, 1984, 1986 |
| Californium-250 | 1970, 1973–1976, 1980 |
| Californium-252 | 1962, 1967–1988 |
| Californium-253 | 1984 |
| Einsteinium-252 | 1970 |
| Einsteinium-253 | 1967–1981, 1984, 1986, 1988 |
| Einsteinium-254 | 1972–1974, 1980, 1982, 1984, 1988 |
| Fermium-255 | 1984, 1988 |
| Fermium-257 | 1968–1977, 1980, 1984, 1986, 1988 |

a. Inventory entries listed as “Eu-152, Eu-154” were compiled as $^{152}$Eu.

# 7.0 FEASIBILITY ANALYSIS

## 7.1 INITIAL EVALUATION

The annual production history for each of the 213 radionuclides in Table 6-4 was compared to the available in vitro bioassay methods for each year (Tables 4-1, 4-2, 4-3, and 4-6) and in vivo bioassay methods (Section 4.0) in each year. The information from the analysis of NOCTS bioassay data (Section 4.2) was incorporated to augment the listing of available methods (namely for gross beta) during periods for which the ORNL dataset does not include those methods. The ORAU Team determined if ORNL had monitoring capability for each radionuclide in each production year by taking into consideration the characteristic radionuclide emissions (type and energy) and analytical method sensitivity (including chemical specificity, radiation type, and energy). The ORAU Team performed this evaluation to identify potential gaps in monitoring capabilities specific to an individual radionuclide. No attempt was made to reconcile the quantity of a specific radionuclide against the frequency at which a particular monitoring method was used.

In this evaluation, when an adequate monitoring method was indicated (i.e., by analytical results for a previous year), it was deemed adequate evidence for concluding there was no gap in monitoring capability. This was the case even when a particular radionuclide was produced in a later year in which no instances of that bioassay method were evident. That is, once a bioassay method was reported, it was assumed to be available each year thereafter. For example, $^{35}$S was produced each year between 1955 and 1969 but analytical results for methods capable of detecting $^{35}$S were only reported in 1955, 1958, 1959, and 1961 (Table 7-1). The lack of recorded monitoring results for the other years of interest was not considered indicative of a gap in monitoring capability.

Tables 7-2 and 7-3 provide a summary of the results of the monitoring capability evaluation. Color and letter codes in Tables 7-2 and 7-3 identify specific radionuclides in inventory, indicate if a bioassay method was available to detect the radionuclide, and specify if sample results for that particular bioassay method are available for that particular year. For instances where dose would be bounded by external radiation (i.e., noble gases), “EXT” is indicated as the bioassay method. As stated in International Commission on Radiological Protection (ICRP) Publication 30, Section 8.2.3, “for submersion in radioisotopes of the noble gases, external irradiation will be of such overriding importance that it alone need be considered” [ICRP 1979].

Table 7-1. Comparison of $^{35}S$ production and number of reported bioassay samples.

| Year | Inventory (Ci) | S-35 samples reported |
|---|---|---|
| 1955 | 57 | 1 |
| 1956 | 14 | 0 |
| 1957 | 67 | 0 |
| 1958 | 88 | 1 |
| 1959 | 60 | 1 |
| 1960 | 23 | 0 |
| 1961 | 150 | 1 |
| 1962 | 70 | 0 |
| 1963 | 29 | 0 |
| 1964 | 100 | 0 |
| 1965 | 14 | 0 |
| 1966 | 83 | 0 |
| 1967 | 0.1 | 0 |
| 1968 | 0.1 | 0 |
| 1969 | 0.01 | 0 |

In Tables 7-2 and 7-3, colors and letters mean:

- Green or G
  - A specific radionuclide was present in inventory in the specified year; and
  - A bioassay method was available to detect the radionuclide in the specified year; and
  - Sample results for that particular bioassay method are available for the specified year.
- Yellow or Y
  - A specific radionuclide was present in inventory in the specified year; and
  - A bioassay method was available to detect the radionuclide, but no sample results for that particular bioassay method are available for the specified year.
- Red or R
  - A specific radionuclide was present in inventory in the specified year, but an additional analysis was necessary to determine if the nuclide represented an infeasibility from a monitoring perspective.
- No color or N
  - No radionuclide was present in inventory in the specified year.

Of the 213 identified radionuclides, the ORAU Team determined that the ORNL HP program was able to monitor for 179 of them using an existing monitoring method (green or yellow shading, or coded as [G] or [Y]). For these 179 radionuclides, no further analysis was required. Attachment B summarizes the radiological properties and monitoring capability decisions for these nuclides.

Table 7-2. Results of feasibility analysis for 1955 to 1969.[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen-3 | HY3 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Beryllium-7 | SC[b] | R | N | R | R | R | N | N | G | N | G | N | N | N | N | G |
| Carbon-11 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Carbon-14 | 000(C-14); 013/GB0;C14 | G | G | G | G | G | G | G | G | G | G | G | G | Y | G | G |
| Sodium-22 | 013/GB0;SC | G | G | N | N | N | N | G | G | G | G | N | N | N | N | N |
| Sodium-24 | 013/GB0;004;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | N | N |
| Magnesium-28 | SC | N | N | N | N | N | N | N | N | N | N | N | G | N | N | G |
| Phosphorus-32 | 000(P-32); PH2 | G | G | G | G | G | G | G | G | G | G | G | Y | Y | N | N |
| Phosphorus-33 | 013/GB0 | N | N | N | N | N | N | N | N | N | G | G | N | Y | G | G |
| Sulfur-35 | 000(S-35);001 | G | Y | Y | G | G | Y | G | Y | Y | Y | Y | Y | Y | G | Y |
| Chlorine-36 | 000(Cl-36); 013/GB0 | G | G | G | G | G | G | G | G | G | G | G | G | Y | G | G |
| Chlorine-38 | 013/GB0 | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Argon-37 | EXT | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Potassium-40 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Potassium-42 | 013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | N | N | N |
| Potassium-43 | SC | N | N | N | N | N | N | N | N | N | G | G | N | G | N | N |
| Calcium-41 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Calcium-45 | 000(Ca-45); 013/GB0 | G | G | G | G | G | G | G | G | G | G | G | G | N | N | N |
| Calcium-47 | 013/GB0;SC | N | N | N | N | N | G | G | G | G | G | G | G | G | G | G |
| Scandium-46 | 013/GB0; FU0; SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Scandium-49 | 013/GB0; FU0 | G | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Titanium-44 | 013/GB0 | N | G | N | G | N | N | N | N | N | N | N | N | N | N | N |
| Vanadium-48 | SC | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N |
| Chromium-51 | 000(Cr-51); SC[c] | R | R | R | R | R | R | R | G | G | G | G | G | G | N | N |
| Manganese-52 | 013/GB0 | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N |
| Manganese-54 | 010;SC[c] | R | R | R | N | N | G | N | N | G | G | G | N | N | N | N |
| Iron-55 | 000(Fe-55)[c] | R | R | N | N | R | R | R | R | R | R | R | R | N | N | N |
| Iron-59 | 000(Fe-59); 013/GB0;009;SC | G | G | N | G | G | G | G | G | G | G | G | G | G | N | N |
| Cobalt-56 | SC | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |
| Cobalt-57 | 000(Co-57); SC[c] | R | R | R | N | N | N | N | N | N | G | N | N | N | N | N |
| Cobalt-58 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | N | N | N | N |
| Cobalt-60 | 000(Co-60); 013/GB0;002;CO0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Nickel-63 | 013/GB0 | G | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Nickel-66 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Copper-64 | 013/GB0 | G | G | G | G | G | G | G | G | G | G | G | G | Y | G | G |
| Copper-67 | SC | N | N | N | N | N | N | N | N | G | G | N | N | G | G | N |
| Zinc-65 | 000(Zn-65); 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |

Table 7-2. Results of feasibility analysis for 1955 to 1969 (continued).[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zinc-69m | GB0 | N | N | N | N | N | N | N | N | N | N | N | N | Y | N | N |
| Gallium-67 | 000(Ga-67); SC[c] | N | N | N | R | R | N | N | N | N | N | N | N | N | N | G |
| Gallium-68 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gallium-72 | 013/GB0; SC | G | N | G | N | N | G | G | G | G | G | G | G | G | G | G |
| Arsenic-71 | 013/GB0 | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N |
| Arsenic-72 | 013/GB0 | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N |
| Arsenic-74 | 007; 013/GB0;SC | N | N | G | G | G | N | G | N | N | N | G | N | N | N | N |
| Arsenic-76 | 013/GB0;SC | N | G | G | N | G | G | G | G | G | G | G | G | G | N | N |
| Arsenic-77 | 013/GB0 | N | G | G | N | G | G | G | G | G | G | G | G | N | N | N |
| Selenium-75 | SC[c] | R | R | R | N | R | R | R | G | G | G | G | G | N | N | N |
| Bromine-82 | 008, 0013/GB013;SC | N | G | G | G | G | G | G | G | G | G | G | G | G | N | N |
| Bromine-85 | 013/GB0 | N | N | N | N | N | N | N | N | G | N | N | N | N | N | N |
| Krypton-85 | EXT | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Rubidium-83 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G |
| Rubidium-84 | SC | N | N | N | N | N | N | N | N | N | G | G | N | N | N | G |
| Rubidium-86 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Rubidium-88 | SC | N | N | N | N | N | N | N | N | N | G | N | N | N | N | N |
| Strontium-82 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Strontium-85 | SR5; SC[c] | R | N | R | R | R | G | Y | G | G | G | G | G | Y | N | N |
| Strontium-87m | SC[c] | N | N | N | N | N | R | N | N | N | G | N | N | N | N | N |
| Strontium-89 | SR0;SR9; 013/GB0; | G | G | G | N | G | G | G | G | G | N | G | G | G | G | G |
| Strontium-90 | SR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Yttrium-86 | SC | N | N | N | N | N | N | N | N | N | G | N | N | N | G | N |
| Yttrium-88 | 000(Y-88); 013/GB0; FU0;SC | N | N | G | G | N | N | G | G | G | N | G | N | N | N | N |
| Yttrium-90 | 000(Y-90); FU0 | N | G | G | G | G | G | G | G | G | G | G | G | G | Y | N |
| Yttrium-91 | 013/GB0; FU0 | G | G | G | N | G | G | G | G | G | G | G | G | G | Y | G |
| Zirconium-95 | 000(Zr-95)005; 013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Zirconium-97 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-90 | 013/GB0 | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-92 | SC | N | N | N | N | N | N | N | N | G | N | N | N | N | N | N |
| Niobium-92m | SC | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |
| Niobium-95 | 000(Nb-95); 005; 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Molybdenum-93 | (c) | N | N | R | N | N | N | N | R | N | N | N | N | N | N | N |
| Molybdenum-99 | 013/GB0;SC | N | N | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Technetium-95m | 013/GB0;SC | N | N | G | G | N | N | N | N | N | N | N | N | G | N | N |

Table 7-2. Results of feasibility analysis for 1955 to 1969 (continued).[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Technetium-99 | 000(Tc-99); 006; 013/GB0 | G | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Technetium-99m | SC | N | N | N | N | N | N | N | N | N | N | N | G | N | G | N |
| Ruthenium-97 | 013/GB0 | N | N | N | N | G | G | N | G | N | N | N | N | N | N | N |
| Ruthenium-103 | 000(Ru-103); SC[c] | R | R | R | N | R | R | R | G | G | G | G | G | G | G | G |
| Ruthenium-105 | 013/GB0 | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Ruthenium-106 | 000(Ru-106); 013/GB0; RU6 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Rhodium-102 | 013/GB0 | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N |
| Palladium-103 | (c) | N | N | N | N | N | N | N | R | N | R | N | N | N | N | N |
| Palladium-109 | 013/GB0 | N | N | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Silver-110m | 013/GB0;018;SC | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |
| Silver-111 | 013/GB0 | N | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Cadmium-109 | 000(Cd-109)[c] | N | N | R | R | N | R | R | N | R | R | R | R | N | N | N |
| Cadmium-115 | 013/GB0 | G | G | N | N | N | G | N | G | G | G | G | G | N | N | N |
| Cadmium-115m | 013/GB0 | G | G | N | N | N | G | G | G | G | G | G | G | N | N | N |
| Indium-111 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G |
| Indium-114 | 013/GB0 | G | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Indium-114m | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tin-113 | SC[c] | R | R | R | N | G | G | G | G | G | G | G | G | G | N | N |
| Tin-117m | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tin-119m | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Antimony-122 | 013/GB0;SC | N | G | N | N | G | G | G | G | G | G | G | G | G | G | N |
| Antimony-124 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | N | N |
| Antimony-125 | 013/GB0;015;SC | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |
| Tellurium-121 | (c) | N | N | R | N | N | N | N | N | N | N | N | N | N | N | N |
| Tellurium-132 | SC | N | N | N | N | N | N | N | N | G | N | N | N | N | G | N |
| Iodine-123 | TH | N | N | N | N | N | N | N | N | N | N | G | N | G | G | G |
| Iodine-125 | 000(I-125); I25; TH[c] | N | N | R | N | N | N | R | G | G | G | N | N | N | N | N |
| Iodine-129 | TH | R | R | R | N | R | R | R | G | G | G | G | G | G | G | G |
| Iodine-130 | TH[c] | N | N | N | N | N | R | R | G | G | G | G | G | G | G | G |
| Iodine-131 | 000(I-131); 011; I31; TH[c] | R | R | R | G | Y | Y | G | G | G | G | G | G | G | G | G |
| Iodine-132 | TH | N | N | N | N | N | N | N | N | N | N | N | N | G | G | G |
| Iodine-133 | TH[c] | N | N | N | N | N | N | R | N | N | N | N | N | G | G | N |
| Xenon-127 | EXT | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Xenon-133 | EXT | N | N | N | N | N | G | G | G | G | G | G | G | G | G | G |
| Cesium-131 | (c) | N | N | N | N | N | N | N | N | N | N | R | N | N | N | N |
| Cesium-132 | 000(Cs-132); 012; SC | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N |
| Cesium-134 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |

Table 7-2. Results of feasibility analysis for 1955 to 1969 (continued).[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cesium-137 | CS7;CS0; SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Barium-131 | SR0 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Barium-133 | SC[c] | R | R | R | N | R | R | R | G | G | G | G | G | G | G | G |
| Barium-135m | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Barium-140 | 014;SR0 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | N |
| Lanthanum-140 | 013;FU0;SC | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |
| Cerium-139 | (c) | R | N | R | R | N | N | N | N | N | N | N | N | N | N | N |
| Cerium-141 | 013/GB0;FU0 | G | G | G | N | G | G | G | G | G | G | G | G | N | N | N |
| Cerium-144 | 013/GB0;FU0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Praseodymium-142 | 013/GB0;FU0 | N | G | G | N | G | G | G | G | G | G | G | G | G | G | N |
| Praseodymium-143 | 013/GB0;FU0 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | N |
| Praseodymium-144 | 013/GB0;FU0 | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N |
| Neodymium-140 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G |
| Neodymium-147 | 013/GB0;FU0 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Neodymium-149 | 013/GB0;FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Promethium-145 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | R | N |
| Promethium-146 | 013/GB0;FU0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Promethium-147 | 000(Pm-147); 013/GB0;PM7; FU0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N |
| Promethium-148 | 013/GB0;FU0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Samarium-151 | 013/GB0;FU0; | N | N | N | N | N | N | N | N | N | N | N | N | N | G | G |
| Samarium-153 | 013/GB0;FU0 | N | G | G | N | G | G | G | N | G | G | G | G | G | G | G |
| Europium-152 | 000(Eu-152); SC | N | N | N | N | N | N | N | G | N | N | N | N | N | G | N |
| Europium-155 | 000(Eu-155); 013;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | N |
| Gadolinium-148 | GA0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gadolinium-153 | 000(Gd-153); GD0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Terbium-156 | SC[c] | N | N | N | R | N | N | N | N | N | N | N | N | G | G | N |
| Terbium-158 | FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Dysprosium-157 | FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Dysprosium-159 | (c) | N | N | R | N | N | N | R | N | N | N | N | N | N | N | N |
| Dysprosium-166 | FU0 | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Holmium-156 | FU0; SC | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Holmium-166 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Erbium-171 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thulium-170 | 000(Tm-170);FU0 | N | N | N | N | N | N | N | G | G | G | G | G | G | G | G |
| Thulium-171 | FU0 | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |

Table 7-2. Results of feasibility analysis for 1955 to 1969 (continued).[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ytterbium-169 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Hafnium-181 | 013/GB0 | G | N | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Tantalum-182 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Tungsten-181 | (c) | N | N | R | R | N | N | N | N | N | N | N | N | N | N | N |
| Tungsten-185 | 013/GB0 | G | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Tungsten-187 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Rhenium-186 | 013/GB0 | N | N | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Osmium-185 | SC[c] | N | N | R | N | N | N | N | N | N | N | N | G | N | N | N |
| Osmium-191 | 013/GB0;SC | N | N | G | N | G | G | G | G | G | G | G | G | G | G | G |
| Iridium-192 | 000(Ir-192); 0013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N |
| Iridium-194 | 013/GB0;SC | N | N | N | N | G | N | G | N | G | N | N | N | N | G | N |
| Platinum-195m | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Platinum-197 | SC | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Gold-195 | (c) | N | N | N | N | N | N | R | N | N | N | N | N | N | N | N |
| Gold-198 | 013/GB0; SC | G | N | G | G | G | G | G | G | G | G | G | G | N | N | N |
| Gold-199 | 013/GB0;SC | G | N | G | N | G | G | G | G | G | G | G | G | G | N | N |
| Mercury-197 | SC[c] | N | N | R | R | R | R | R | G | G | G | G | G | N | N | N |
| Mercury-203 | 013/GB0;SC | G | G | G | N | G | G | G | G | G | G | G | G | G | N | N |
| Thallium-201 | 000(Tl-201); SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thallium-204 | 013/GB0;016 | G | G | G | G | G | G | G | G | G | G | G | G | Y | G | G |
| Lead-203 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-206 | (c) | N | N | R | R | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-207 | 013/GB0 | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-210 | 013/GB0 | G | G | G | N | G | G | G | G | G | G | G | G | Y | G | G |
| Polonium-210 | 004;PO0; GU0 | N | N | N | N | N | N | N | G | N | N | N | G | N | N | N |
| Thorium-228 | GU0 | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N |
| Thorium-229 | GF0;TF0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Thorium-230 | GF0;TF0 | N | G | N | N | N | N | N | G | G | N | G | N | G | G | G |
| Thorium-232 | GF0;TF0 | N | N | N | N | N | N | N | N | G | N | N | N | N | G | G |
| Thorium-234 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Protactinium-231 | PF3;PA0 | N | N | N | N | N | N | G | Y | Y | N | Y | Y | N | G | G |
| Protactinium-233 | PA3, SC | N | N | N | N | N | N | N | N | G | G | N | G | N | N | G |
| Uranium-232 | UR0 | N | N | N | N | N | N | G | G | G | G | G | N | N | G | N |
| Uranium-233 | UR0 | N | N | N | N | N | N | G | G | G | N | G | G | G | G | G |
| Uranium-234 | UR0 | N | G | N | N | N | N | G | G | G | N | G | G | G | G | G |
| Uranium-235 | UR0 | G | G | G | N | N | N | G | G | G | N | G | G | G | G | G |
| Uranium-236 | UR0 | G | G | N | N | N | N | G | G | G | N | G | G | G | G | G |
| Uranium-238 | UR0 | G | G | N | N | N | N | G | G | G | G | G | G | G | G | G |

Table 7-2. Results of feasibility analysis for 1955 to 1969 (continued).[a]

| Nuclide | Bioassay method code[b] | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Neptunium-236 | SC | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Neptunium-237 | 017;GU0;NP0; | G | G | G | N | G | N | G | G | N | G | G | N | G | G | N |
| Neptunium-238 | 013/GB0; SC | N | N | N | N | N | N | N | N | N | N | G | G | N | N | N |
| Plutonium-236 | PU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Plutonium-237 | PU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Plutonium-238 | GU0;PU0 | N | N | N | N | N | N | G | G | G | N | G | N | N | G | G |
| Plutonium-239 | GU0;PU9;PU0 | G | G | N | N | N | N | G | G | G | G | G | G | G | G | G |
| Plutonium-240 | GU0;PU0 | N | N | N | N | N | N | G | G | G | G | G | G | N | G | G |
| Plutonium-241 | 000(Pu-241); PU1[c] | R | R | N | N | R | N | N | R | R | R | R | R | G | G | G |
| Plutonium-242 | GU0;PU0 | N | N | N | N | N | N | G | G | G | G | G | G | G | G | G |
| Plutonium-244 | PU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Americium-241 | 000(Am-241);AM0; GUO;TP0 | N | N | N | N | G | G | G | G | G | G | G | G | G | G | G |
| Americium-243 | 000(Am-243); TP0; GF0 | N | N | N | N | N | N | G | G | G | G | G | G | G | G | G |
| Curium-242 | 000(Cm-242); GU0; TP0 | N | N | N | N | N | N | N | G | G | G | G | G | N | G | N |
| Curium-243 | TP0 | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Curium-244 | 000(Cm-244); TP0;CM0 | N | N | N | N | N | N | N | G | G | G | N | G | G | G | G |
| Curium-245 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G |
| Curium-246 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Curium-247 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G |
| Curium-248 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | G |
| Berkelium-249 | 000(Bk-249); TP0 | N | N | N | N | N | N | N | N | N | G | N | N | G | N | G |
| Californium-248 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Californium-249 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | G |
| Californium-250 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Californium-252 | TP0; GU0 | N | N | N | N | N | N | N | G | N | N | N | N | G | G | G |
| Californium-253 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Einsteinium-252 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Einsteinium-253 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | G | G | G |
| Einsteinium-254 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Fermium-255 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Fermium-257 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | G | G |

a. See Section 7.1 for color coding.
b. Bioassay codes defined in Tables 4-1 and 4-2. EXT indicates exposure monitored by external dosimetry, SC indicates monitored by in vivo analysis, TH indicates monitored by in vivo thyroid counting.
c. See discussion in Section 7.2.

Table 7-3. Results of feasibility analysis for 1970 to 1988.[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen-3 | HY3 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Beryllium-7 | SC[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Carbon-11 | SC | N | N | N | N | N | G | N | G | N | G | G | N | N | N | N | N | N | N | N |
| Carbon-14 | 000(C-14); 013/GB0;C14 | G | G | G | G | Y | Y | N | N | N | N | Y | Y | G | Y | N | Y | N | N | N |
| Sodium-22 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Sodium-24 | 013/GB0;004;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Magnesium-28 | SC | G | N | N | N | N | N | N | G | N | N | N | N | N | G | G | N | N | G | G |
| Phosphorus-32 | 000(P-32); PH2 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Phosphorus-33 | 013/GB0 | G | G | Y | G | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | G | Y | Y | Y | N |
| Sulfur-35 | 000(S-35);001 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Chlorine-36 | 000(Cl-36); 013/GB0 | G | G | Y | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Chlorine-38 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Argon-37 | EXT | G | G | N | G | G | G | G | G | G | G | G | G | G | N | N | N | N | N | N |
| Potassium-40 | SC | N | N | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N |
| Potassium-42 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Potassium-43 | SC | N | G | N | G | G | G | G | G | G | N | G | G | N | G | N | N | N | N | N |
| Calcium-41 | (c) | N | N | N | N | N | N | N | R | N | N | N | N | N | N | N | N | R | N | N |
| Calcium-45 | 000(Ca-45); 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Calcium-47 | 013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | N | N | N |
| Scandium-46 | 013/GB0; FU0; SC | G | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Scandium-49 | 013/GB0; FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Titanium-44 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Vanadium-48 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Chromium-51 | 000(Cr-51); SC[c] | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Manganese-52 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Manganese-54 | 010;SC[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Iron-55 | 000(Fe-55)[c] | N | N | N | N | N | N | N | N | N | N | R | R | R | G | Y | Y | Y | N | N |
| Iron-59 | 000(Fe-59); 013/GB0;009;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cobalt-56 | SC | N | N | G | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N |
| Cobalt-57 | 000(Co-57); SC[c] | N | N | G | G | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N |
| Cobalt-58 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cobalt-60 | 000(Co-60); 013/GB0;002;CO 0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Nickel-63 | 013/GB0 | G | G | Y | N | N | N | N | N | Y | N | Y | N | N | N | N | Y | Y | Y | N |
| Nickel-66 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Copper-64 | 013/GB0 | N | N | N | N | N | N | Y | N | N | N | N | N | N | N | N | N | N | N | N |
| Copper-67 | SC | G | G | N | G | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N |
| Zinc-65 | 000(Zn-65); 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Zinc-69m | 013/GB0 | N | N | N | G | Y | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gallium-67 | 000(Ga-67); SC[c] | G | G | G | G | G | G | G | G | G | N | N | N | N | G | N | N | N | N | N |
| Gallium-68 | SC | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gallium-72 | 013/GB0; SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Arsenic-71 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Arsenic-72 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Arsenic-74 | 007; 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Arsenic-76 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Arsenic-77 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Selenium-75 | SC[c] | N | N | N | N | N | N | N | N | N | G | G | G | G | G | G | G | G | N | N |
| Bromine-82 | 008, 0013/GB013;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Bromine-85 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Krypton-85 | EXT | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Rubidium-83 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Rubidium-84 | SC | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Rubidium-86 | 013/GB0;SC | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Rubidium-88 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Strontium-82 | SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Strontium-85 | SR5; SC[c] | Y | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | Y | N | N |
| Strontium-87m | SC[c] | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Strontium-89 | SR0;SR9; 013/ GB0; | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N |
| Strontium-90 | SR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Yttrium-86 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Yttrium-88 | 000(Y-88); 013/GB0; FU0;SC | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Yttrium-90 | 000(Y-90); FU0 | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | Y | Y |
| Yttrium-91 | 013/GB0; FU0 | G | G | G | G | G | G | G | G | G | N | N | N | N | N | N | N | N | N | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zirconium-95 | 000(Zr-95)005; 013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | N |
| Zirconium-97 | SC | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-90 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-92 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-92m | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Niobium-95 | 000(Nb-95); 005; 013/GB0;SC | G | G | G | G | G | G | G | G | G | G | G | G | N | G | G | G | N | N | N |
| Molybdenum-93 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Molybdenum-99 | 013/GB0;SC | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Technetium-95m | 013/GB0;SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Technetium-99 | 000(Tc-99); 006; 013/GB0 | G | N | Y | G | Y | Y | G | G | Y | G | Y | G | G | Y | G | Y | Y | Y | Y |
| Technetium-99m | SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Ruthenium-97 | 013/GB0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Ruthenium-103 | 000(Ru-103); SC[c] | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | N |
| Ruthenium-105 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Ruthenium-106 | 000(Ru-106); 013/GB0; RU6 | G | G | G | G | G | Y | G | G | Y | G | G | G | G | G | G | G | Y | Y | Y |
| Rhodium-102 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Palladium-103 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Palladium-109 | 013/GB0 | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Silver-110m | 013/GB0;018;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Silver-111 | 013/GB0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cadmium-109 | 000(Cd-109)[c] | N | N | R | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cadmium-115 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cadmium-115m | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Indium-111 | SC | G | G | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Indium-114 | 013/GB0 | G | G | Y | G | Y | Y | Y | Y | N | N | N | Y | N | N | N | N | N | N | N |
| Indium-114m | SC | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tin-113 | SC[c] | N | N | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N |
| Tin-117m | SC | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N |
| Tin-119m | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | R | N | N |
| Antimony-122 | 013/GB0;SC | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Antimony-124 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Antimony-125 | 013/GB0;015;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tellurium-121 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tellurium-132 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Iodine-123 | TH | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Iodine-125 | 000(I-125); I25; TH[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Iodine-129 | TH | G | G | G | G | G | G | G | G | G | Y | Y | Y | Y | Y | Y | Y | G | G | G |
| Iodine-130 | TH[c] | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N | Y | N | N | N |
| Iodine-131 | 000(I-131); 011; I31; TH[c] | G | G | G | G | G | G | G | N | G | Y | Y | N | N | Y | N | Y | G | N | G |
| Iodine-132 | TH | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Iodine-133 | TH[c] | N | N | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N |
| Xenon-127 | EXT | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N | N | G | G |
| Xenon-133 | EXT | G | G | G | G | G | G | G | N | G | G | G | N | N | N | N | N | N | N | N |
| Cesium-131 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cesium-132 | 000(Cs-132); 012; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cesium-134 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cesium-137 | CS7;CS0; SC | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Barium-131 | SR0 | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Barium-133 | SC[c] | G | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Barium-135m | SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |
| Barium-140 | 014;SR0 | G | G | G | G | G | G | G | G | G | N | G | G | N | G | N | N | N | N | N |
| Lanthanum-140 | 013;FU0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N |
| Cerium-139 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cerium-141 | 013/GB0;FU0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Cerium-144 | 013/GB0;FU0;SC | G | G | G | G | G | G | G | G | G | G | N | G | G | G | G | G | G | G | G |
| Praseodymium-142 | 013/GB0;FU0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Praseodymium-143 | 013/GB0;FU0 | G | N | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Praseodymium-144 | 013/GB0;FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Neodymium-140 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Neodymium-147 | 013/GB0;FU0 | G | G | G | G | N | N | N | N | N | Y | N | N | N | N | N | N | N | N | N |
| Neodymium-149 | 013/GB0;FU0 | N | N | N | N | N | N | N | N | N | Y | N | N | N | N | N | N | N | N | N |
| Promethium-145 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Promethium-146 | 013/GB0;FU0; SC | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Promethium-147 | 000(Pm-147); 013/GB0;PM7; FU0 | G | G | G | G | G | G | G | G | G | Y | G | Y | Y | Y | G | G | Y | G | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Promethium-148 | 013/GB0;FU0; SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Samarium-151 | 013/GB0;FU0; | G | G | G | G | G | G | G | G | G | Y | G | Y | Y | N | G | G | Y | Y | N |
| Samarium-153 | 013/GB0;FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Europium-152 | 000(Eu-152); SC | N | N | N | N | G | G | N | N | G | G | G | G | N | N | G | G | N | N | G |
| Europium-155 | 000(Eu-155); 013;SC | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gadolinium-148 | GA0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gadolinium-153 | 000(Gd-153); GD0; SC | N | G | N | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Terbium-156 | SC[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Terbium-158 | FU0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Dysprosium-157 | FU0 | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Dysprosium-159 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Dysprosium-166 | FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | Y | N | N | N | N |
| Holmium-156 | FU0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Holmium-166 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Erbium-171 | 013/GB0 | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thulium-170 | 000(Tm-170);FU0 | G | G | N | N | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thulium-171 | FU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Ytterbium-169 | SC | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N | N | G | N | N |
| Hafnium-181 | 013/GB0 | G | G | Y | G | Y | Y | Y | Y | N | Y | Y | N | N | N | N | N | N | N | N |
| Tantalum-182 | 013/GB0;SC | G | G | G | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tungsten-181 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tungsten-185 | 013/GB0 | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Tungsten-187 | 013/GB0;SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Rhenium-186 | 013/GB0 | G | G | G | N | N | N | N | N | N | Y | N | N | N | N | N | N | N | N | N |
| Osmium-185 | SC[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Osmium-191 | 013/GB0;SC | G | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Iridium-192 | 000(Ir-192); 0013/GB0;SC | G | G | N | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Iridium-194 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Platinum-195m | SC | N | N | G | G | G | N | N | N | G | N | N | N | N | N | N | N | N | N | N |
| Platinum-197 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gold-195 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gold-198 | 013/GB0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Gold-199 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Mercury-197 | SC[c] | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Mercury-203 | 013/GB0;SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thallium-201 | 000(Tl-201); SC | N | N | N | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thallium-204 | 013/GB0;016 | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Lead-203 | SC | N | N | G | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-206 | (c) | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-207 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Bismuth-210 | 013/GB0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Polonium-210 | PO0; GU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thorium-228 | GU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Thorium-229 | GF0;TF0 | G | G | N | G | G | N | N | G | N | G | G | G | G | G | Y | Y | G | N | Y |
| Thorium-230 | GF0;TF0 | G | G | G | G | G | G | G | N | G | G | G | G | G | G | Y | Y | G | Y | Y |
| Thorium-232 | GF0;TF0; | N | N | G | G | G | G | G | N | G | G | G | G | G | G | Y | Y | G | Y | N |
| Thorium-234 | 013/GB0 | N | N | N | N | N | N | N | N | N | N | N | Y | N | N | N | N | N | N | N |
| Protactinium-231 | PF3;PA0 | N | N | N | N | N | N | Y | G | Y | Y | Y | Y | N | N | Y | Y | Y | N | N |
| Protactinium-233 | PA3, SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Uranium-232 | UR0 | G | G | N | N | G | G | G | G | G | G | N | N | N | N | N | N | N | N | N |
| Uranium-233 | UR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Uranium-234 | UR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Uranium-235 | UR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Uranium-236 | UR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Uranium-238 | UR0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Neptunium-236 | SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Neptunium-237 | 017;GU0;NP0; | G | N | G | Y | Y | Y | Y | Y | G | G | Y | Y | Y | Y | Y | Y | Y | Y | N |
| Neptunium-238 | 013/GB0; SC | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Plutonium-236 | PU0 | G | N | N | G | N | G | N | N | N | N | N | G | N | N | G | N | G | N | N |
| Plutonium-237 | PU0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | G | N | N |
| Plutonium-238 | GU0;PU0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | G | G |
| Plutonium-239 | GU0;PU9;PU0 | G | G | G | N | G | G | G | G | G | G | G | G | G | G | G | G | N | G | G |
| Plutonium-240 | GU0;PU0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | G |
| Plutonium-241 | 000(Pu-241); PU1[c] | G | G | G | G | G | Y | N | G | G | G | Y | G | G | G | G | G | Y | N | N |
| Plutonium-242 | GU0;PU0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Plutonium-244 | PU0 | G | G | G | G | G | G | G | G | G | G | G | G | G | N | N | N | N | N | N |
| Americium-241 | 000(Am-241); AM0; GUO; TP0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Americium-243 | 000(Am-243); TP0 | G | G | G | G | G | G | G | G | G | N | G | G | G | G | G | G | G | N | G |
| Curium-242 | 000(Cm-242); TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |

Table 7-3. Results of feasibility analysis for 1970 to 1988 (continued).[a]

| Nuclide | Bioassay method code[b] | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Curium-243 | TP0 | N | N | G | G | N | G | G | N | N | N | N | G | G | G | N | N | N | N | N |
| Curium-244 | 000(Cm-244); TP0;CM0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Curium-245 | TP0 | N | N | G | G | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N |
| Curium-246 | TP0 | G | G | N | G | N | N | N | G | N | N | N | N | N | N | N | N | N | N | G |
| Curium-247 | TP0 | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Curium-248 | TP0 | G | G | G | G | G | G | G | G | G | G | G | N | G | G | G | N | G | N | G |
| Berkelium-249 | 000(Bk-249); TP0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | N | G | N | G |
| Californium-248 | TP0 | N | N | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Californium-249 | TP0 | G | G | G | G | G | G | G | N | N | G | G | G | G | N | G | N | G | N | N |
| Californium-250 | TP0 | G | N | N | G | G | G | G | N | N | N | G | N | N | N | N | N | N | N | N |
| Californium-252 | TP0 | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G | G |
| Californium-253 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N | N | N |
| Einsteinium-252 | TP0 | G | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| Einsteinium-253 | TP0 | G | G | G | G | G | G | G | G | G | G | G | G | N | N | G | N | G | N | G |
| Einsteinium-254 | TP0 | N | N | G | G | G | N | N | N | N | N | G | N | G | N | G | N | N | N | G |
| Fermium-255 | TP0 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | G | N | N | N | G |
| Fermium-257 | TP0 | G | G | G | G | G | G | G | G | N | N | G | N | N | N | G | N | G | N | G |

a. See Section 7.1 for color coding.
b. Bioassay codes defined in Tables 4-1 and 4-2. EXT indicates exposure monitored by external dosimetry, SC indicates monitored by in vitro analysis, TH indicates monitored by in vitro thyroid counting.
c. See discussion in Section 7.2.

In the case of 34 of the 213 radionuclides (Table 7-4), the ORAU Team concluded that additional evaluations were necessary to determine if the nuclides represented an infeasibility from a monitoring perspective. Table 7-4 provides a summary of the radiological properties of these 34 radionuclides. An analysis and evaluation of the monitoring capability of 28 of these 34 radionuclides is provided in Section 7.2. Separate analyses for five of the remaining six (radioiodines) are provided in a separate document specifically targeting assignment of internal dose from radioiodine exposure. The one remaining (Pu-241) was processed and handled on the Y-12 campus. Because associated exposure would have occurred at the Y-12 campus further analysis will be included in a Y-12 specific evaluation.

Table 7-4. Thirty-four radionuclides identified as needing additional evaluation.[a]

| Nuclide | Production years | Half life | Decay mode[b] | Photon energy[c] (keV) | Electron energy[d] (keV) |
|---|---|---|---|---|---|
| Beryllium-7 | 1955, 1957–1959, 1962, 1964, 1969 | 53.3 d | EC | 49.3 | 0 |
| Calcium-41 | 1977, 1986 | 1.4E5 yr | EC | 0.4 | 2.3 |
| Chromium-51 | 1955–1967, 1975 | 27.7 d | EC | 32.5 | 3.8 |
| Manganese-54 | 1955–1957, 1960, 1963–1965 | 312.5 d | EC | 836 | 4.2 |
| Iron-55 | 1955–1956, 1959–1966, 1980–1986 | 2.7 yr | EC | 1.6 | 4.2 |
| Cobalt-57 | 1955–1957, 1964, 1972–1976 | 270.9 d | EC | 125.2 | 18.6 |
| Gallium-67 | 1958–1959, 1969–1978, 1983 | 78.26 hr | EC | 158 | 35.5 |
| Selenium-75 | 1955–1957, 1959–1966, 1979–1986 | 119.8 d | EC | 394.2 | 14.5 |
| Strontium-85 | 1955, 1957–1967, 1970, 1986 | 64.84 d | EC | 511.8 | 8.9 |
| Strontium-87m | 1960, 1964, 1970 | 2.8 hr | EC | 320.3 | 66.9 |
| Molybdenum-93 | 1957, 1962 | 3.5E3 yr | EC | 10.6 | 5.5 |
| Ruthenium-103 | 1955–1957, 1959–1986 | 39.28 d | EC | 468.7 | 74.8 |
| Palladium-103 | 1962, 1964 | 16.96 d | EC | 14.4 | 5.8 |
| Cadmium-109 | 1957–1958, 1960–1961, 1963–1966, 1972 | 464 d | EC | 26.3 | 82.6 |
| Tin-113 | 1955–1957, 1959–1967, 1979 | 115.1 d | EC | 22.8 | 6.3 |
| Tin-119m | 1986 | 293 d | IT | 11.4 | 77.7 |
| Tellurium-121 | 1957 | 17 d | EC | 577.3 | 9.9 |
| Iodine-125 | 1957, 1961–1964 | 60.1 d | EC | 42 | 19.3 |
| Iodine-129 | 1955–1957, 1959–1988 | 1.57E7 yr | β– | 24.6 | 63.8 |
| Iodine-130 | 1960–1972, 1985 | 12.36 hr | β– | 2,138.5 | 297.2 |
| Iodine-131 | 1955–1976, 1978–1980, 1983, 1985–1986, 1988 | 8.04 d | β– | 381.5 | 191.7 |
| Iodine-133 | 1961, 1967–1968, 1977 | 20.8 hr | β– | 607.1 | 410.6 |
| Cesium-131 | 1965 | 9.69 d | EC | 22.8 | 6.5 |
| Barium-133 | 1955–1957, 1959–1972 | 10.74 yr | EC | 401.9 | 54.2 |
| Cerium-139 | 1955, 1957–1958 | 137.66 d | EC | 159.5 | 35.5 |
| Promethium-145 | 1968 | 17.7 yr | EC | 31 | 14 |
| Terbium-156 | 1958, 1967–1968 | 5.34 d | EC | 1,826 | 103.1 |
| Dysprosium-159 | 1957, 1961 | 144.4 d | EC | 45 | 12.8 |
| Tungsten-181 | 1957–1958 | 121.2 d | EC | 40.4 | 10.8 |
| Osmium-185 | 1957, 1966 | 94 d | EC | 718.9 | 19.2 |
| Gold-195 | 1961 | 183 d | EC | 84.6 | 50.7 |
| Mercury-197 | 1957–1966 | 64.1 hr | EC | 70 | 66.4 |
| Bismuth-206 | 1957–1958 | 6.24 d | EC | 3,278.1 | 135.8 |
| Plutonium-241 | 1955–1956, 1959, 1962–1975, 1977–1986 | 14.4 yr | β– | 0 | 5.2 |

a. Radiological properties in this table are from Radiological Toolbox [Eckerman and Shoreen 2013].
b. EC = decay by electron capture, IT = decay by isomeric transition, β– = decay by beta emission.
c. Emitted photon and X-ray energy per transformation.
d. Emitted beta, conversion electron, and auger electron energy per transformation.

## 7.2 ADDITIONAL EVALUATION

As indicated in Table 7-5, below, 28 of the 34 radionuclides requiring additional evaluation all decay by either electron capture or isomeric transformation and generally have short half-lives (22 of the 28 have half-lives of less than 1 year).

Table 7-5. Derived air concentration values for 28 radionuclides requiring further evaluation.

| Nuclide | DCF (Sv/Bq)[a] | DAC[b] (μCi/cm$^3$) |
|---|---|---|
| Beryllium-7 | 4.2E−10 | 1.2E−05 |
| Calcium-41 | 2.5E−09 | 3.0E−06 |
| Chromium-51 | 2.5E−10 | 1.6E−05 |
| Manganese-54 | 7.3E−09 | 4.7E−07 |
| Iron-55 | 7.5E−09 | 6.1E−07 |
| Cobalt-57 | 3.7E−09 | 9.4E−07 |
| Gallium-67 | 1.7E−09 | 2.0E−06 |
| Selenium-75 | 7.5E−09 | 3.3E−07 |
| Strontium-85 | 5.6E−09 | 8.8E−07 |
| Strontium-87m | 6.0E−10 | 1.6E−05 |
| Molybdenum-93 | 2.8E−08 | 4.0E−07 |
| Ruthenium-103 | 1.5E−08 | 2.6E−07 |
| Palladium-103 | 1.7E−09 | 1.9E−06 |
| Cadmium-109 | 2.3E−07 | 5.9E−08 |
| Tin-113 | 1.3E−08 | 3.0E−07 |
| Tin-119m | 1.1E−08 | 3.8E−07 |
| Tellurium-121 | 5.4E−09 | 1.1E−06 |
| Cesium-131 | 7.5E−10 | 1.3E−05 |
| Barium-133 | 9.6E−09 | 3.1E−07 |
| Cerium-139 | 1.0E−08 | 4.0E−07 |
| Promethium-145 | 4.1E−08 | 2.3E−07 |
| Terbium-156 | 1.4E−08 | 4.0E−07 |
| Dysprosium-159 | 2.6E−09 | 2.3E−06 |
| Tungsten-181 | 4.4E−10 | 1.3E−05 |
| Osmium-185 | 7.1E−09 | 4.0E−07 |
| Gold-195 | 8.3E−09 | 4.7E−07 |
| Mercury-197 | 3.6E−08 | 1.3E−07 |
| Bismuth-206 | 2.4E−08 | 2.7E−07 |

a. Most limiting inhalation dose conversion factor (Sv/Bq) from ICRP Publication 68 [ICRP 1994].
b. Calculated derived air concentration (DAC) based on contemporary ICRP [1994] DCFs. Corresponds to the air concentration that, if breathed at the standard rate (1.2 m$^3$/hr) for 2,000 hr/yr, will result in a dose equivalent of 5 rem.

Table 7-5 lists the limiting derived air concentration (DAC) values based on solubility for each of the 28 radionuclides under evaluation in this discussion. These values range from $1.6 \times 10^{-5}$ μCi/cm$^3$ ($^{87m}$Sr) to $5.9 \times 10^{-8}$ μCi/cm$^3$ ($^{109}$Cd). For comparison purposes, before publication of National Bureau of Standards (NBS) Handbook 69 in 1961 the tolerance value for airborne beta/gamma activity in ORNL facilities was set at $1 \times 10^{-7}$ μCi/cm$^3$. Respiratory protection was required for entry above 10% of this limit ($1 \times 10^{-8}$ μCi/cm$^3$). By 1961, the maximum permissible concentration (MPC) concept within NBS Handbook 69 [NBS 1959] was adopted. The MPC for occupational exposure to unidentified beta/gamma emitters was set at $1 \times 10^{-9}$ μCi/cm$^3$ [Hart 1960] with trigger levels remaining at 0.1 MPC ($1 \times 10^{-10}$ μCi/cm$^3$) for general entry without respiratory protection [UCC 1961]. Information on the DAC values associated with the radionuclides shown in Table 7-5 along with the general standards in place at the time is provided to illustrate the culture around radiation safety at the time of production of

these exotics. For example, pre NBS, the respiratory protection requirements were set at values less than the DACs for the nuclides shown in Table 7-5. Post NBS, the standard was even more protective than the DACs shown in Table 7-5.

An evaluation of the dosimetric consequences of each of the 28 radionuclides requiring further analysis was conducted. The committed dose to the maximally exposed organ from inhalation of $1 \times 10^{-5}$ of the total annual inventory was computed for the year with the maximum recorded inventory (Table 7-6). The factor $1 \times 10^{-5}$ was selected based on the guidance in NUREG-1400, which postulates that $1 \times 10^{-6}$ times the material handled could serve as a reasonable estimate of the quantity that could be inhaled [Hickey et al. 1993]. A factor of 10 was added to ensure a conservative evaluation. The organ dose conversion factor (mrem/mCi) for the organ with the highest unit dose per intake was selected from ICRP [1994], as shown in the table. Although inventory quantities were not available for six radionuclides ($^{93}$Mo, $^{103}$Pd, $^{139}$Ce, $^{156}$Tb, $^{185}$Os, and $^{206}$Bi), dose consequences (50-year committed dose equivalent) from inhalation of a significant fraction of the annual inventory for the remainder range from 0.3 mrem to 1,464 mrem to the maximally exposed organ. It should be noted that the inventory quantity for $^{55}$Fe in this calculation did not consider the inventory during 1980 through 1982, during which values were as high as $1 \times 10^{6}$ mCi (a factor of 1,600 higher than in previous years). The intake quantity calculated using the analysis method would predict an intake quantity of 0.1 Ci, which corresponds to an air activity of $4 \times 10^{-5}$ μCi/ml. Exposure to this concentration of $^{55}$Fe without detection by workplace monitoring controls does not seem credible, considering the fact that the manufacturing process for $^{55}$Fe would also carry over a small percentage of $^{59}$Fe (an easily detected beta/gamma emitter). The ORNL radioisotope production manual indicates that $^{59}$Fe is produced by the same production mechanism as $^{55}$Fe (irradiation of $^{54}$Fe) and lists its presence at <5%.

As indicated in Section 4.2, ORNL had an active bioassay program from the earliest period under evaluation (1955) and routinely performed analyses for tritium, polonium, plutonium, radium, strontium, uranium, gross alpha, and gross beta. When necessary, additional methods were developed to meet emergent sampling needs. Such supplemental sampling was coded specifically to the analyte (codes 001–018, as defined in Table 4-1) or was given a more general “000” code (or 0F0 for fecal analysis).

Table 4-3 lists all of the analytes associated with the 1584 code “000” sample results that are known to exist (based on the ORNL bioassay database; [UT-Battelle 2013]). This listing is potentially incomplete because it is known that not all bioassay results were recorded into the bioassay database (see the discussion in Section 4.2). However, at one point bioassay analyses specific to eight of the 28 radionuclides under evaluation ($^{51}$Cr, $^{54}$Mn, $^{55}$Fe, $^{57}$Co, $^{67}$Ga, $^{85}$Sr, $^{103}$Ru, and $^{109}$Cd) were performed. Table 7-7 indicates the frequency of these samples.

Table 7-6. Dosimetric analysis of radionuclides.

| Nuclide | Maximum annual inventory (mCi) | Maximum organ DCF[a] (mrem/mCi) | Organ[a] | Dose to organ from annual inhalation of $1 \times 10^{-5}$ time inventory[b] (mrem) |
|---|---|---|---|---|
| Beryllium-7 | 533 | 1,554 | Extrathoracic airways | 8 |
| Calcium-41 | 501 | 9,250 | Bone surface | 46 |
| Chromium-51 | 46,225 | 925 | Extrathoracic airways | 428 |
| Manganese-54 | 115 | 27,010 | Extrathoracic airways | 31 |
| Iron-55 | 620[c] | 27,750 | Spleen | 172 |
| Cobalt-57 | 175 | 13,690 | Lungs | 24 |
| Gallium-67 | 120 | 6,290 | Extrathoracic airways | 8 |
| Selenium-75 | 2,160 | 27,750 | Kidneys | 599 |
| Strontium-85 | 142 | 20,720 | Extrathoracic airways | 29 |
| Strontium-87m | 84 | 2,220 | Extrathoracic airways | 2 |
| Molybdenum-93 | (d) | 103,600 | Bone surface | (d) |
| Ruthenium-103 | 1,020 | 55,500 | Lungs | 566 |
| Palladium-103 | (d) | 6,290 | Extrathoracic airways | (d) |
| Cadmium-109 | 64 | 851,000 | Kidneys | 545 |
| Tin-113 | 610 | 48,100 | Lungs | 293 |
| Tin-119m | 3,598 | 40,700 | Lungs | 1464 |
| Tellurium-121 | (d) | 19,980 | Extrathoracic airways | (d) |
| Cesium-131 | 25(e) | 2,775 | Extrathoracic airways | 1 |
| Barium-133 | 80 | 35,520 | Bone surface | 28 |
| Cerium-139 | (d) | 37,000 | Lungs | (d) |
| Promethium-145 | 32 | 151,700 | Bone surface | 49 |
| Terbium-156 | (d) | 51,800 | Extrathoracic airways | (d) |
| Dysprosium-159 | 60 | 9,620 | Bone surface | 6 |
| Tungsten-181 | 18 | 1,628 | Extrathoracic airways | 0.3 |
| Osmium-185 | (d) | 26,270 | Extrathoracic airways | (d) |
| Gold-195 | 5.6 | 30,710 | Lungs | 2 |
| Mercury-197 | 542 | 133,200 | Lungs | 722 |
| Bismuth-206 | (d) | 88,800 | Extrathoracic airways | (d) |

a. DCFs are based on ICRP [1994], obtained from the Radiological Toolbox. While DCFs are provided for a multitude of individual organs, the highest value (along with the associated organ) is listed and was used in subsequent calculations.
b. The calculated values represents the 50-year committed dose to the organ listed based on an intake of 1E-05 times the listed inventory quantity.
c. Inventory quantities for 1980 to 1982 were not included in analysis.
d. No Inventory data are available for one or more years for these radionuclides.
e. Inventory data based on parent nuclide (Ba-131).

Table 7-7. Number of bioassay samples collected for code 000 analytes by year.[a]

| Analytical method code (radionuclide) | Production years | 1960 | 1964 | 1965 | 1968 | 1969 | 1970 | 1971 | 1973 | 1976 | 1978 | 1983 | 1987 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 000 (Cr) | 1955–1967, 1975 | NS | 2 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 000 (Cr-51) | 1955–1967, 1975 | NS | 1 | NS | 2 | NS | NS | NS | NS | 1 | NS | NS | NS |
| 010 (Mn-54) | 1955–1957, 1960, 1963–1965 | 2 | NS | NS | NS | NS | NS | NS | NS | NS | 1 | NS | NS |
| 000 (Fe-55) | 1955–1956, 1959–1966, 1980–1986 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | 5 | NS |
| 000 (Co-57) | 1955–1957, 1964, 1972–1976 | NS | NS | 2 | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 000 (Ga-66/67) | 1958–1959, 1969–1978, 1983 | NS | NS | NS | NS | NS | 5 | NS | NS | NS | NS | NS | NS |
| 000 (Ga-67) | 1958–1959, 1969–1978, 1983 | NS | NS | NS | 2 | NS | NS | 1 | NS | NS | NS | NS | NS |
| SR5 (Sr-85) | 1955, 1957–1967, 1970, 1986 | 3 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | 8 |
| 000 (Ru-103) | 1955–1957, 1959–1986 | NS | NS | 2 | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| 000 (Ru-103/106) | 1955–1957, 1959–1986 | NS | NS | NS | NS | 4 | NS | NS | NS | NS | NS | NS | NS |
| 000 (Cd-109) | 1957–1958, 1960–1961, 1963–1966, 1972 | NS | NS | NS | NS | NS | NS | NS | 1 | NS | NS | NS | NS |

a. NS = No samples collected.

## 8.0 SUMMARY

ORNL isotope production involved a wide array of radioactive materials it termed *exotics*. NIOSH developed an ORNL radionuclide inventory by reviewing shipping records, sales reports, and selected logbooks. This inventory was compared to available bioassay data and available bioassay methods. This study did not evaluate if ORNL workers were properly monitored but rather if bioassay technology deficiencies existed that would result in improper monitoring.

The ORAU Team compared the available bioassay date from the ORNL internal monitoring database with the data provided by ORNL as contained within Energy Employee Occupational Illness Compensation Program Act claimant files. With the exception of gross beta analysis (results of which seem to be missing from the ORNL database between 1955 and 1959), the sample frequency in the ORNL and NOCTS datasets are comparable, although the NOCTS data files tend to be more complete. The results are consistent with the conclusion of the ORNL Internal Dosimetry staff that the database is incomplete and might be missing up to 25% of the bioassay samples [ORAUT 2013], albeit comparison between NOCTS and the ORNL database indicates a slightly lower value based on the qualitative evaluation in this document.

Exotics that ORNL HP could not readily detect by gross alpha or beta/gamma methods would have presented a particular monitoring challenge. This report identifies 28 radionuclides that might have presented such a monitoring challenge. Evaluation of the ORNL HP bioassay program confirmed the ability of ORNL Staff to develop specialized bioassay methods as needed to adapt to changing conditions and emergent situations. Although no monitoring evidence has been found for the 28 identified nuclides, it remains clear that ORNL Staff had the capability for developing methods had they become necessary. The combination of the inventory and radiological dose coefficients for these 28 radionuclides allowed the development of bounding potential intakes (see Table 7-6) for these radionuclides. These bounding intakes could be used as the basis for a plausible estimation of dose from these radionuclides.

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# ATTACHMENT A
# SUMMARY OF IN VITRO BIOASSAY METHODS

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**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

## A.1 GROSS ANALYSIS METHODS

### A.1.1 Gross Alpha

The ORAU Team observed gross alpha bioassays in the dataset as far back as 1951, and found a 1957 procedure describing gross alpha urinalysis [Brown et al. 1957]. The method includes a bismuth phosphate lanthanum fluoride precipitation of the raw urine with the sample dried for alpha counting.

A 1978 gross alpha fecal method describes the following sequence: drying the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and electrodepositing of the sample for alpha counting [Henley 1978].

### A.1.2 Gross Beta

Gross beta bioassays were observed in the dataset from as far back as 1954, but reports indicate that gross beta urine measurements were performed as early as 1948.

The first instance of a basic procedure for gross beta urinalysis was indicated in a 1948 memorandum [Farabee 1948a]. During the procedure, a 50-mL urine sample was taken, the organic material was destroyed, the inorganic residue was deposited on a watch glass, and the total activity was determined. A note states that some of the activity may be due to potassium being present.

The first more-comprehensive procedure for gross beta urinalysis was issued in 1968 [Henley 1968]. This method was used to estimate the beta activity in urine exclusive of the naturally occurring $^{40}K$. Two alternative methods were identified: (1) a precipitation using calcium phosphate, or (2) a nitric acid and hydrogen peroxide solution. Both methods involve transferring the precipitate to a beta-counting planchet, drying, and beta-counting.

Changes in the process occurred in 1978, based on either a precipitation using a nitric acid phosphoric acid solution or a nitric acid and ruthenium carrier solution. Both methods indicate transferring the precipitate to a beta-counting planchet, drying, and beta-counting [Henley 1978].

Note: Adjustment of results based on the beta emission energy for a specific radionuclide may be necessary when the emission energy for the suspected radionuclide is sufficiently different than the emission energy for the calibration source. Henley reported that gross beta counting systems were calibrated using Sr-90 [Henley 1978, p. 65].

### A.1.3 Fission Products

Fission product bioassays were observed in the dataset from as far back as 1951, but reports indicate that a procedure for strontium urine measurements was in place as early as 1949 [Tompkins et al. 1949]. A total of 17 fission product urine samples were in the dataset through 1958. The ORAU Team found no official fission product procedure for this period, but it appears that a rare-earth and alkaline-earth procedure might have been used for fission products based on process knowledge of the target radionuclide; this procedure is discussed in the next section.

Note: Adjustment of results based on the beta emission energy for a specific radionuclide may be necessary when the emission energy for the suspected radionuclide is sufficiently different than the emission energy for the calibration source. Henley reported that gross beta counting systems were calibrated using Sr-90 [Henley 1978, p. 65].

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

### A.1.4 Rare Earth

Rare-earth elements include the 15 lanthanides as well as scandium and yttrium. The lanthanides include cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, terbium, thulium, and ytterbium. Rare-earth bioassays were observed in the dataset as far back as 1951, but reports indicate that a procedure for rare-earth urine measurements was in place as early as 1949.

The first basic procedure for rare- and alkaline-earth element urinalysis was issued in 1949 [Tompkins et al. 1949]. The method describes a coprecipitation of the rare- and alkaline-earth elements with calcium phosphate from an alkaline solution, separation of the phosphoric acid from the cations by ion exchange, and finally a separation of barium, strontium, and rare-earth elements from calcium and magnesium by a chromate precipitation. The final precipitate was filtered on a medium porosity glass filter, dried, and counted in a standard beta/gamma counting chamber.

The ORAU Team observed changes in the process based on a procedure issued in 1968 [Henley 1968]. This method was based on a precipitation from an acid solution of ashed urine salts as the oxalate. The oxalate was oxidized using perchloric acid and sodium bromate. The precipitate was then transferred to a beta-counting planchet, dried, and beta-counted.

Rare-earth fecal (RF0) sampling was performed beginning as early as 1955. Seventy rare-earth fecal samples were in the dataset through 1972. No method could be identified.

Note: Adjustment of results based on the beta emission energy for a specific radionuclide may be necessary when the emission energy for the suspected radionuclide is sufficiently different than the emission energy for the calibration source. Henley reported that gross beta counting systems were calibrated using Sr-90 [Henley 1978, p. 65].

### A.1.5 Transplutonium

Transplutonium urine bioassays were observed from as far back as 1958. The first procedure for transplutonium urinalysis was issued in 1968 [Henley 1968]. The method was improved by performing transplutonium separation using ion-exchange methods with neptunium elution using hydrochloric acid. The sample was then eluted, evaporated, and alpha-counted.

Two methods were identified from 1978 based on (1) extraction chromatography, or (2) bismuth phosphate ion exchange [Henley 1978]. Both methods involve transferring the precipitate to a stainless-steel counting disk, drying, and alpha-counting.

The extraction chromatography method used an extraction column to extract the actinide and lanthanide elements. The basic phosphate precipitate was eluted with a nitric acid and aluminum phosphate solution and passed through an extraction column. The solution was then transferred to a watch glass, dried, and alpha-counted.

The bismuth phosphate method uses a basic phosphate precipitate or a hydrochloric acid effluent from an ion exchange column. After the plutonium, uranium, neptunium, and protactinium were removed from the basic phosphate precipitate by ion exchange, the column effluent would contain any trivalent actinides. A rare-earth carrier and hydrofluoric acid were added. The precipitate was then transferred to a stainless-steel disk, dried, and alpha-counted.

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

The fecal sample method identified from 1978 involved drying the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and deposit of the sample for alpha-counting [Henley 1978].

## A.2 ELEMENT-SPECIFIC ANALYSIS METHODS

### A.2.1 Barium

One barium-specific bioassay was observed in the dataset in 1961, but reports indicate that a procedure for barium and the rare-earth elements was in place as early as 1949 [Tompkins et al. 1949]. The method involved a coprecipitation of the rare- and alkaline-earth elements with calcium phosphate from an alkaline solution, separation of the phosphoric acid from the cations by ion exchange, and finally a separation of barium, strontium, and rare-earth elements from calcium and magnesium by a chromate precipitation. The final precipitate was filtered on a medium-porosity glass filter, dried, and counted in a standard beta/gamma counting chamber.

The ORAU Team observed that changes in the process occurred in 1955 based on ion exchange and the eluting of strontium and barium with nitric acid. The final precipitate was deposited to a counting dish, dried, and counted in a standard beta/gamma counting chamber. This method was used for both barium and strontium analysis [Farabee 1955; Brown et al. 1957].

Process improvements occurred in 1968 and again in 1978 based on ion exchange and the eluting of strontium and barium with nitric acid. The final precipitate was deposited to a counting dish, dried, and counted in a standard beta/gamma counting chamber. It was noted that this method was used for both $^{89}Sr$ and $^{90}Sr$ in urine. Residue was deposited, dried, and beta-counted in a low-background counter. If the presence of radiobarium and radium was suspected, identification could be made by spectral analysis [Henley 1968, 1978].

### A.2.2 Cesium

Cesium bioassays were observed in the dataset from as far back as 1955, and reports indicate that a procedure for cesium urine measurements was in place as early as 1956 [Morgan 1956]. A total of 1,873 cesium urine samples are in the dataset through 1988. In this method, cesium (along with potassium) was precipitated from a dilute acid solution as a cobalt nitrite. This precipitate was dissolved in nitric acid and a cesium phosphotungstate precipitation separated the cesium from potassium. The cesium was finally precipitated for counting. The precipitate was then transferred to a counting planchet, dried, and beta-counted.

A 1968 report describes a method in which cesium (along with potassium) was precipitated from a dilute acid solution [Henley 1968]. A 1978 report describes a method in which cesium (along with potassium) was precipitated from a dilute acid solution as a cobalt nitrite [Henley 1978]. The 1978 method remained mostly the same as the 1968 method.

### A.2.3 Cobalt

Cobalt bioassays were observed in the dataset from as far back as 1954. The first basic procedure for cobalt urinalysis was issued in 1968 [Henley 1968]. In concentrations of 6-molar HCl, cobalt ions formed a complex of sufficient strength to be absorbed by ion exchange resins. Then the cobalt was eluted with HCl, dried, and beta-counted. A 1978 report describes a cobalt urine method that was mostly the same as the 1968 method [Henley 1978].

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

### A.2.4 Neptunium

Neptunium bioassays were observed from as far back as 1962. A total of 64 neptunium-specific urine samples were in the dataset through 1979, although neptunium might also have been measured using the gross alpha procedure.

The first procedure for neptunium urinalysis was issued in 1968 [Henley 1968]. The method was improved by performing neptunium separation using ion exchange methods with neptunium elution using HCl. The sample was then eluted, evaporated, electrodeposited, and alpha-counted.

The 1978 neptunium fecal method involved drying of the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and electrodeposit of the sample for alpha-counting [Henley 1978].

Gross alpha fecal sampling was performed, possibly for neptunium, beginning as early as 1955.

### A.2.5 Plutonium

The first procedure for plutonium urinalysis at ORNL was implemented in 1946. The method involved precipitating bismuth phosphate from urine, dissolving the precipitate, reprecipitating bismuth phosphate, oxidizing the organic matter, and finally precipitating $LaF_3$. The sample was then deposited on a platinum disk, dried, and alpha-counted [Farabee 1946].

In 1947, the method improved but remained mostly the same as the 1946 method [Farabee 1947].

In January 1957, a method was described that involved using a precipitation of calcium oxalate from urine, oxidation of the organic matter, and a final $LaF_3$ precipitation [Brown et al. 1957]. The sample was deposited on a platinum disk, dried, and alpha-counted.

In 1968, the method was improved by performing plutonium separation using ion exchange methods with plutonium elution using HCl [Henley 1968]. The sample was then eluted, evaporated, and electrodeposited for counting.

Plutonium-specific fecal sampling was performed beginning in 1968. The fecal sample method identified in 1978 involved drying the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and electrodeposit of the sample for alpha-counting [Henley 1978].

### A.2.6 Plutonium-241

The first basic procedure for $^{241}Pu$ urinalysis was issued in 1957 [Henley 1968]. This method was based on urine samples that were treated with HCl. The plutonium, neptunium, uranium, protactinium, and transplutonium elements were adsorbed on an anion exchange resin column. The plutonium was eluted from the column with HCl and transferred to a glass cylinder. Toluene was added to the sample and then counted for low-energy beta using a liquid scintillation counter.

Another report [Henley 1978] describes another method from 1978. This method was based on urine samples that were treated with HCl. The plutonium elements were adsorbed on an anion exchange resin column. The plutonium was eluted from the column with HCl and transferred to a glass cylinder.

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

Toluene was added to the sample and the counted for low-energy beta using a liquid scintillation counter. The method remained mostly the same as the 1968 method.

### A.2.7 Polonium

The first basic procedure for polonium urinalysis was issued in 1957 [Brown et al. 1957]. This method was based on urine samples treated with HCl and the polonium plated onto clean copper disks suspended in the solution for 2 hours. Deposition of the polonium was done by electrolysis. The alpha activity was determined by counting both sides of the disks.

Another report describes a method in which polonium was quantitatively deposited on a nickel disk from HCl [Henley 1968]. The salt of the ashed urine sample was dissolved in a dichloric acid and a clean nickel disk was suspended in the solution for 2 hours. Deposition of the polonium was by electrolysis. The alpha activity was determined by counting both sides of the disks.

Another report [Henley 1978] describes a method in which the polonium was quantitatively deposited on a nickel disk from HCl. The salt of the ashed urine sample was dissolved in a dichloric acid and a clean nickel disk was suspended in the solution for 2 hours. Deposition of the polonium was by electrolysis. The alpha activity was determined by counting both sides of the disks. The method remained mostly the same as the 1968 method.

### A.2.8 Protactinium

Protactinium bioassays were observed from as far back as 1962. From 1952 to 1975, 189 protactinium urine samples were in the dataset. Note that protactinium might also have been measured using the gross alpha procedure.

The initial method involved an extraction of niobium and protactinium from the raw urine using nitric and HCl solutions. A protactinium separation was performed using oxalic acid with the sample transferred to a stainless-steel planchet, dried, and beta-counted [Henley, no date].

Changes in the process occurred in 1968 [Henley 1968]. The method was improved by performing protactinium separation using ion exchange methods with protactinium elution using HCl. The sample was then eluted, evaporated, and alpha-counted.

Further changes in the process occurred in 1978 [Henley 1978]. The method included an extraction of niobium and protactinium from the raw urine using nitric and hydrochloric acid solutions. A protactinium separation was performed using oxalic acid with the sample then transferred to a stainless-steel planchet, dried, and beta-counted.

### A.2.9 Radium

Radium bioassays were observed in the dataset from as far back as 1954, but reports indicate that a procedure for radium urine measurements was in place as early as 1948 [Farabee 1948b]. A total of 330 radium-in-urine samples were in the dataset from 1954 to 1987.

The first basic procedure for radium urinalysis was issued in 1948 [Farabee 1948b]. The referenced method, CH-3534, could not be found, but a beta/gamma counting of the decay products in the urine was performed at approximately 12 days of ingrowth, at which time the percent of progeny in equilibrium with radium and radon was 88.5%.

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

The first basic procedure for radium urinalysis found was issued in 1957. This method involved an extraction based on HCl and sulfuric acid solutions. The precipitate was then transferred to a lacquered platinum disk, dried, and counted. If the activity was found to be greater than 1 cpm, a count was performed at a 1- or 2-day interval to determine which isotope was present [Brown et al. 1957].

### A.2.10 Strontium

Strontium bioassays were observed in the dataset from as far back as 1951, but reports indicate that a procedure for strontium urine measurements was in place as early as 1949 [Tompkins et al. 1949].

A report from April 15, 1950, indicates that an analysis procedure for strontium was in use [Morgan and Western 1950]. The report notes that the 1949 procedure was in use but recommended a change that would separate strontium from calcium and magnesium by a strontium nitrate precipitation using a nitric acid solution. The report noted that 18 samples had been assayed for strontium by using this procedure.

Another report, from July 20, 1951, indicates that an analysis procedure for strontium was in use [Morgan 1951]. The report notes that the procedure was lengthy and included the elements of barium, strontium, yttrium, lanthanum, and other rare earths.

Changes in the process occurred in 1955 based on ion exchange and the eluting of strontium and barium with nitric acid. The final precipitate was deposited to a counting dish, dried and counted in a standard beta/gamma counting chamber. This method was for both barium and strontium analysis [Farabee 1955; Brown et al. 1957].

Improvements in the process occurred in 1968 based on ion exchange and the eluting of strontium and barium with nitric acid. The final precipitate was deposited to a counting dish, dried, and counted in a standard beta/gamma counting chamber. It was noted that this method was for both $^{89}Sr$ and $^{90}Sr$ in urine. Residue was deposited, dried, and beta-counted in a low-background counter. If the presence of radiobarium and radium was suspected, identification could be made by spectral analysis [Henley 1968].

Fecal bioassays specific to $^{90}Sr$ were observed in the dataset from 1960. The fecal sample method identified in 1978 involved drying of the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and deposition of the sample for beta-counting [Henley 1978].

### A.2.11 Thorium

No thorium-specific fecal sampling was identified. However, gross alpha fecal sampling could have been performed for thorium beginning as early as 1955.

One thorium fecal sample method was identified in 1978 [Henley 1978]. It involved drying of the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and electrodeposition of the sample for alpha-counting.

**ATTACHMENT A**
**SUMMARY OF IN VITRO BIOASSAY METHODS (continued)**

### A.2.12 Tritium

Tritium urine bioassays were observed as far back as 1953. No early tritium method was identified, but it is thought that a procedure was used that was based on an Argonne National Laboratory method extant around 1950 [Western 1950].

The first procedure for tritium urinalysis was issued in 1968 [Henley 1968]. In this method, tritium samples were counted by liquid scintillation. Urine samples were analyzed by either distilling the sample and counting a portion of the distillate for tritium beta, or by adding the raw urine directly to the scintillation mix.

Another method for tritium urinalysis was issued in 1978 [Henley 1978]. The method remained mostly the same as the 1968 method.

### A.2.13 Uranium

Uranium bioassays were observed from as far back as 1949. A total of 15,100 uranium urine samples were in the dataset from 1949 through 1988. Only basic information is available for the methods used from 1947 to 1949. In 1949, a procedure was developed that describes the separation and elution for uranium [Morgan and Western 1949]. The sample was transferred to a platinum plate, evaporated, and counted on a standard alpha counter. The overall recovery of 80% to 85% was typical for $^{233}U$. In 1951, improvements were be developed to minimize the time necessary to complete the procedure [Morgan and Western 1951].

In January 1957, a method using tributyl phosphate in hexane was in use [Brown et al. 1957]. In this method, the uranium was separated, transferred to a stainless-steel disk, dried, and alpha-counted.

In 1968, the method was improved by performing uranium separation using ion exchange methods with uranium elution using HCl [Henley 1968]. The sample was then eluted, evaporated, and electrodeposited for counting.

Gross alpha fecal sampling was performed for uranium beginning as early as 1955. The fecal sample method (from 1978) involved drying the fecal sample, treatment with an acid solution, separation using ion exchange resins, evaporation of the final product, and electrodeposition of the sample for alpha-counting [Henley 1978].

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS

The following 179 radionuclides required no further analysis to determine there is no infeasibility in respect to ORNL's monitoring capabilities. Nuclear decay information was generally obtained from the ICRP Publication 38 [ICRP 1983] nuclear decay data contained within the Radiological Toolbox [Eckerman and Shoreen 2006]. Nuclear decay information for Br-85 and Es-252 were obtained from the National Nuclear Data Center (NuDat) dataset [National Nuclear Data Center, no date; ORAU 2000] as these radionuclides are not in ICRP Publication 38.

**Americium-241**

- Production years: 1959–1988
- Half-life: 432 yr
- Decay mode: α
- Progeny: Np-237
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,440 | 13.0% |
| alpha | 5,490 | 84.7% |
| gamma | 59.5 | 35.9% |

- Bioassay method: transplutonium (TP0) in urine, GF0 (gross alpha fecal)

**Americium-243**

- Production years: 1961–1978, 1980–1986, 1988
- Half-life: 7,370 yr
- Decay mode: α
- Progeny: Np-239
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,230 | 11.0% |
| alpha | 5,280 | 87.6% |
| gamma | 74.7 | 68.2% |

- Bioassay method: transplutonium (TP0) in urine and GF0 (gross alpha fecal)

**Antimony-122**

- Production years: 1956, 1959–1968, 1971, 1987
- Half-life: 2.7 d
- Decay mode: EC, β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 521 | 67.2% |
| beta | 771 | 25.7% |
| gamma | 564 | 70.7% |

- Bioassay method: gross beta (013) then whole body counting

**Antimony-124**

- Production years: 1955–1957, 1959–1967
- Half-life: 60.2 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 194 | 52.2% |
| beta | 918 | 22.4% |
| gamma | 603 | 98.3% |
| gamma | 723 | 10.8% |
| gamma | 1,690 | 47.8% |

- Bioassay method: gross beta (013) then whole body counting

**Antimony-125**

- Production years: 1955–1957, 1959–1966
- Half-life: 2.7 yr
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 24.9 | 13.4% |
| beta | 34.7 | 17.9% |
| beta | 86.9 | 40.4% |
| beta | 215 | 13.6% |
| X-ray | 27.5 | 26.6% |
| gamma | 428 | 29.8% |
| gamma | 463 | 10.6% |
| gamma | 601 | 17.8% |
| gamma | 636 | 11.3% |

- Bioassay method: gross beta (013) then whole body counting, Sb-125 specific method (015) used in 1962 and 1963, radiation from daughter Te-125m

**Argon-37**

- Production years: 1955–1957, 1959–1971, 1973–1982
- Half-life: 35.04 d
- Decay mode: EC
- Progeny: stable
- Important energy emissions: NA
- Bioassay method: NA-noble gas: external monitoring is controlling for these materials

**Arsenic-71**

- Production years: 1960
- Half-life: 65.3 hr
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 352 | 28.0% |
| gamma | 175 | 82.0% |
| gamma | 511 | 56.7% |

- Bioassay method: gross beta (013)

**Arsenic-72**

- Production years: 1960

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 26 hr
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 1,120 | 64.2% |
| positron | 1,530 | 16.3% |
| gamma | 511 | 176.0% |
| gamma | 834 | 79.5% |

- Bioassay method: gross beta (013)

**Arsenic-74**

- Production years: 1957–1959, 1961, 1965
- Half-life: 17.77 d
- Decay mode: EC, β+, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 243 | 15.4% |
| positron | 408 | 26.0% |
| beta | 531 | 18.6% |
| gamma | 511 | 58.1% |
| gamma | 596 | 59.4% |
| gamma | 635 | 15.4% |

- Bioassay method: gross beta (013) then whole body counting

**Arsenic-76**

- Production years: 1956–1957, 1959–1967
- Half-life: 25.9 hr
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 993 | 35.3% |
| beta | 1,260 | 51.1% |
| gamma | 559 | 45.0% |

- Bioassay method: gross beta (013) then whole body counting

**Arsenic-77**

- Production years: 1956–1957, 1959–1966
- Half-life: 38.8 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 229 | 97% |

- Bioassay method: gross beta (013 and GB0)

**Barium-131**

- Production years: 1955–1957, 1959–1971
- Half-life: 11.5 d
- Decay mode: EC
- Progeny: Cs-131
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 3.45 | 79.1% |
| A.E. | 4.17 | 24.4% |
| I.C. | 87.8 | 17.9% |
| gamma | 216 | 19.7% |
| gamma | 373 | 14.0% |
| gamma | 496 | 46.8% |

- Bioassay method: strontium (SR0)

**Barium-135m**

- Production years: 1970, 1986
- Half-life: 28.7 hr

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Decay mode: IT
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 231 | 59.9% |
| I.C. | 262 | 11.3% |
| X-ray | 31.8 | 15.5% |
| X-ray | 32.2 | 28.9% |
| gamma | 268 | 15.6% |

- Bioassay method: in vivo counting

**Barium-140**

- Production years: 1955–1957, 1959–1968, 1970–1978, 1980–1981, 1983
- Half-life: 12.75 d
- Decay mode: β-
- Progeny: La-140
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 141 | 23.9% |
| beta | 344 | 38.2% |
| beta | 362 | 24.1% |
| I.C. | 23.7 | 56.0% |
| I.C. | 28.8 | 12.9% |
| gamma | 30 | 14.1% |
| gamma | 537 | 24.4% |

- Bioassay method: strontium (SR0), Ba-140 specific method (014) used one time in 1961

**Berkelium-249**

- Production years: 1964, 1967, 1969–1984, 1986, 1988
- Half-life: 330 d
- Decay mode: SF, β-, α
- Progeny: Am-245

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 32.4 | 100% |

- Bioassay method: transplutonium (TPO)

**Bismuth-207**

- Production years: 1957
- Half-life: 32.9 yr
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 10.4 | 16.1% |
| X-ray | 73 | 21.8% |
| X-ray | 75.3 | 36.6% |
| gamma | 570 | 97.8% |
| gamma | 1,060 | 74.6% |

- Bioassay method: gross beta (013)

**Bismuth-210**

- Production years: 1955–1957, 1959–1970
- Half-life: 5.01 d
- Decay mode: β-
- Progeny: Po-210
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 389 | 100% |

- Bioassay method: gross beta (013 and GB0)

**Bromine-82**

- Production years: 1956–1967
- Half-life: 35.3 hr
- Decay mode: β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 138 | 97.0% |
| gamma | 554 | 70.8% |
| gamma | 619 | 43.4% |
| gamma | 698 | 28.5% |
| gamma | 777 | 83.5% |
| gamma | 828 | 24.0% |
| gamma | 1,040 | 27.2% |
| gamma | 1,320 | 26.5% |
| gamma | 1,470 | 16.3% |

- Bioassay method: gross beta (013), Br-82/Br-83 (008) then whole body counting; Br-82 specific method used in 1960 and 1961

**Bromine-85**

- Production year: 1963
- Half-life: 2.9 min
- Decay mode: β-
- Progeny: Kr-85m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 1,070 | 95.7% |

- Bioassay method: gross beta

**Cadmium-115**

- Production years: 1955–1956, 1960, 1962–1966
- Half-life: 53.46 hr
- Decay mode: β-
- Progeny: In-115m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 184 | 33.0% |
| beta | 394 | 62.5% |
| gamma | 528 | 27.5% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: gross beta (013 and GB0), radiation from daughter In-115m.

**Cadmium-115m**

- Production years: 1955–1956, 1960–1966
- Half-life: 44.6 d
- Decay mode: β-
- Progeny: In-115
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 618 | 97% |
| gamma | 934 | 2% |

- Bioassay method: gross beta (013 and GB0), radiation from daughter In-115m

**Calcium-45**

- Production years: 1955–1966
- Half-life: 162.7 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 77.2 | 100% |

- Bioassay method: gross beta (013 and GB0)

**Calcium-47**

- Production years: 1960–1984
- Half-life: 4.54 d
- Decay mode: β-
- Progeny: Sc-47
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 243 | 80.9% |
| beta | 819 | 19.0% |
| gamma | 1,300 | 74.6% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: gross beta (013) then whole body counting, radiation from daughter Sc-47

**Californium-248**

- Production years: 1972
- Half-life: 334 d
- Decay mode: SF, α
- Progeny: Cm-244
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,220 | 19.6% |
| alpha | 6,260 | 80.0% |

- Bioassay method: transplutonium (TP0)

**Californium-249**

- Production years: 1968–1976, 1979–1982, 1984, 1986
- Half-life: 351 yr
- Decay mode: SF, α
- Progeny: Cm-245
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,810 | 82.4% |
| I.C. | 31.0 | 13.6% |
| I.C. | 35.8 | 10.5% |
| gamma | 333 | 14.6% |
| gamma | 388 | 66.0% |

- Bioassay method: transplutonium (TP0)

**Californium-250**

- Production years: 1970, 1973–1976, 1980
- Half-life: 13.08 yr
- Decay mode: SF, α
- Progeny: Cm-246

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,990 | 15.0% |
| alpha | 6,030 | 84.6% |

- Bioassay method: transplutonium (TP0)

**Californium-252**

- Production years: 1962, 1967–1988
- Half-life: 2.638 yr
- Decay mode: SF, α
- Progeny: Cm-248
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,080 | 15.2% |
| alpha | 6,120 | 81.5% |
| beta | 1,280 | 19.2% |

- Bioassay method: transplutonium (TP0) Gross Alpha (GU0), Cf-252 specific method 1989–1992

**Californium-253**

- Production years: 1984
- Half-life: 17.81 d
- Decay mode: β-, α
- Progeny: Cm-249, Es-253
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 65.5 | 49.8% |
| beta | 79.1 | 49.8% |
| A.E. | 12.3 | 10.2% |
| I.C. | 19.6 | 32.9% |

- Bioassay method: transplutonium (TP0)

**Carbon-11**

- Production years: 1975, 1977, 1979–1980
- Half-life: 20.39 min

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 386 | 99.8% |
| gamma | 511 | 200% |

- Bioassay method: whole body counting

**Carbon-14**

- Production years: 1955–1975, 1980–1983, 1985
- Half-life: 5,700 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 49.5 | 100% |

- Bioassay method: gross beta (013 and GB0), C-14 specific methods 1986–1992

**Cerium-141**

- Production years: 1955–1957, 1959–1966, 1970
- Half-life: 32.5 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 130 | 69.7% |
| beta | 181 | 30.3% |
| I.C. | 103 | 18.9% |
| gamma | 145 | 48.3% |

- Bioassay method: rare earths (FU0)

**Cerium-144**

- Production years: 1955–1979, 1981–1988

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Half-life: 284.9 d
- Decay mode: β-
- Progeny: Pr-144m, Pr-144
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 50.3 | 19.6% |
| beta | 91.3 | 76.6% |
| gamma | 134 | 11.1% |

- Bioassay method: rare earths (FU0), whole body counting, Ce-144 specific method

**Cesium-132**

- Production years: 1962
- Half-life: 6.5 d
- Decay mode: EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| Gamma | 668 | 97.5 |

- Bioassay method: nuclide specific method (012), whole body counting

**Cesium-134**

- Production years: 1955–1957, 1959–1966
- Half-life: 2.06 yr
- Decay mode: EC, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 23.1 | 27.3% |
| beta | 210 | 70.2% |
| gamma | 569 | 15.4% |
| gamma | 605 | 97.6% |
| gamma | 796 | 85.5% |

- Bioassay method: gross beta (013) then whole body counting

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Cesium-137**

- Production years: 1955–1988
- Half-life: 30.16 yr
- Decay mode: β-
- Progeny: Ba-137m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 174 | 94.4% |
| gamma[a] | 662 | 100.0% |

a. See Comments below.

- Bioassay method: Cs-137 specific method (CS7) then whole body counting
- Comments: 662 keV gamma is from daughter Ba-137m

**Chlorine-36**

- Production years: 1955–1972
- Half-life: 3.01E5 yr
- Decay mode: EC, β+, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 278 | 98.1% |

- Bioassay method: gross beta (013 and GB0)

**Chlorine-38**

- Production years: 1956
- Half-life: 37.2 min
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 420 | 31.9% |
| beta | 1,180 | 10.5% |
| beta | 2,240 | 57.6% |
| gamma | 1,640 | 31.9% |
| gamma | 2,170 | 42.4% |

- Bioassay method: gross beta (013); only production year in pre-existing SEC

**Cobalt-56**

- Production years: 1967, 1972, 1977
- Half-life: 77.2 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 631 | 18.1% |
| gamma | 511 | 38.0% |
| gamma | 847 | 99.9% |
| gamma | 1,240 | 66.9% |
| gamma | 1,770 | 15.5% |
| gamma | 2,600 | 17.3% |

- Bioassay method: whole body counting

**Cobalt-58**

- Production years: 1955–1957, 1959–1965
- Half-life: 70.86 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 201 | 14.9% |
| gamma | 511 | 29.8% |
| gamma | 811 | 99.5% |

- Bioassay method: gross beta (013) then whole body counting

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Cobalt-60**

- Production years: 1955–1988
- Half-life: 5.27 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 95.9 | 99.9% |
| gamma | 1,170 | 99.9% |
| gamma | 1,330 | 100.0% |

- Bioassay method: gross beta (013) then whole body counting, Co-60-specific method used in 1962–1964

**Copper-64**

- Production years: 1955–1969, 1976
- Half-life: 12.7 hr
- Decay mode: EC, β+, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 190 | 39.0% |
| positron | 278 | 17.4% |
| gamma | 511 | 34.8% |

- Bioassay method: gross beta (013 and GB0)

**Copper-67**

- Production years: 1963–1964, 1967–1968, 1970–1971, 1973–1976
- Half-life: 61.83 hr
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 116 | 56.9% |
| beta | 149 | 22.0% |
| beta | 184 | 20.0% |
| I.C. | 83.7 | 12.1% |
| gamma | 93.3 | 16.1% |
| gamma | 185 | 48.7% |

- Bioassay method: whole body counting

**Curium-242**

- Production years: 1962–1966, 1968, 1986
- Half-life: 162.8 d
- Decay mode: SF, α
- Progeny: Pu-238
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,070 | 25.9% |
| alpha | 6,110 | 74.1% |

- Bioassay method: transplutonium (TP0)

**Curium-243**

- Production years: 1965, 1972–1973, 1975–1976, 1981–1983
- Half-life: 29.1 yr
- Decay mode: α, EC
- Progeny: Pu-239, Am-243

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,740 | 11.5% |
| alpha | 5,790 | 72.6% |
| A.E. | 10.7 | 28.2% |
| A.E. | 14.2 | 14.6% |
| I.C. | 106 | 23.3% |
| I.C. | 155 | 17.5% |
| X-ray | 18.4 | 13.8% |
| X-ray | 100 | 14.7% |
| X-ray | 104 | 23.3% |
| gamma | 228 | 10.6% |
| gamma | 278 | 14.0% |

- Bioassay method: transplutonium (TP0)

**Curium-244**

- Production years: 1962–1964, 1966–1988
- Half-life: 18.1 yr
- Decay mode: SF, α
- Progeny: Pu-240
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,760 | 23.6% |
| alpha | 5,800 | 76.4% |

- Bioassay method: transplutonium (TP0), Cm-242/244 specific method (CM0) used in 1986–1988

**Curium-245**

- Production years: 1969, 1972–1973, 1986
- Half-life: 8,500 yr
- Decay mode: α
- Progeny: Pu-241

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,362 | 92.9% |
| I.C. | 52.6 | 44.6% |
| X-ray | 18.4 | 11.1% |
| X-ray | 100 | 21.6% |
| X-ray | 104 | 34.2% |

- Bioassay method: transplutonium (TP0)

**Curium-246**

- Production years: 1970–1971, 1973, 1977, 1988
- Half-life: 4,760 yr
- Decay mode: SF, α
- Progeny: Pu-242
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,340 | 17.8% |
| alpha | 5,390 | 82.2% |

- Bioassay method: transplutonium (TP0)

**Curium-247**

- Production years: 1969, 1972
- Half-life: 1.56E+07 yr
- Decay mode: α
- Progeny: Pu-243
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,870 | 71.0% |
| alpha | 5,270 | 13.8% |
| gamma | 402 | 72.0% |

- Bioassay method: transplutonium (TP0)

**Curium-248**

- Production years: 1968–1980, 1982–1984, 1986, 1988
- Half-life: 3.48E+05 yr

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Decay mode: SF, α
- Progeny: Pu-244
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,030 | 16.5% |
| alpha | 5,080 | 75.0% |
| beta | 1,370 | 55.9% |
| gamma | 1,100 | 12.2% |

- Bioassay method: transplutonium (TP0)

**Dysprosium-157**

- Production years: 1975
- Half-life: 8.1 hr
- Decay mode: EC
- Progeny: Tb-157
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| X-ray | 43.8 | 24.2% |
| X-ray | 44.6 | 43.3% |
| gamma | 326 | 92.0% |

- Bioassay method: rare earth (FU0)

**Dysprosium-166**

- Production years: 1965, 1984
- Half-life: 81.6 hr
- Decay mode: β-
- Progeny: Ho-166
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 118 | 89.1% |
| I.C. | 18.9 | 14.1% |
| I.C. | 26.8 | 54.6% |
| I.C. | 46.2 | 10.6% |
| X-ray | 46.8 | 14.8% |
| X-ray | 47.6 | 26.3% |
| gamma | 82.5 | 13.8% |

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Bioassay method: rare earth (FU0)

**Einsteinium-252**

- Production years: 1970
- Half-life: 471.7 d
- Decay mode: α, EC
- Progeny: Bk-248
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,562 | 10.6% |
| alpha | 6,632 | 62.6% |
| A.E. | 11.2 | 15.2% |
| X-ray | 15.7 | 18.8% |
| gamma | 139 | 11.7% |
| gamma | 785 | 15.4% |

- Bioassay method: gross alpha

**Einsteinium-253**

- Production years: 1967–1981, 1984, 1986, 1988
- Half-life: 20.47 d
- Decay mode: SF, α
- Progeny: Bk-249
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,630 | 89.8% |

- Bioassay method: transplutonium (TP0)

**Einsteinium-254**

- Production years: 1972–1974, 1980, 1982, 1984, 1988
- Half-life: 275.7 d
- Decay mode: α
- Progeny: Bk-250

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,430 | 93.4% |
| A.E. | 11.5 | 43.9% |
| A.E. | 15.4 | 23.4% |
| I.C. | 10.2 | 31.7% |
| I.C. | 16.0 | 16.2% |
| I.C. | 17.3 | 66.3% |
| I.C. | 30.5 | 14.9% |
| I.C. | 37.6 | 18.2% |
| X-ray | 15.3 | 32.1% |

- Bioassay method: transplutonium (TP0)

**Erbium-171**

- Production years: 1973
- Half-life: 7.52 hr
- Decay mode: β-
- Progeny: Tm-171
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 362 | 94.3% |
| I.C. | 52.1 | 39.5% |
| gamma | 112 | 20.5% |
| gamma | 296 | 28.9% |
| gamma | 308 | 64.4% |

- Bioassay method: gross beta (Sr-90) (GB0) as production in years of pre-existing SEC

**Europium-152**

- Production years: 1962, 1968, 1974–1975, 1978–1981, 1984–1985, 1988
- Half-life: 13.53 yr
- Decay mode: β-, EC, β+
- Progeny: Au-152

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 222 | 13.8% |
| I.C. | 74.9 | 19.4% |
| X-ray | 40.2 | 38.3% |
| gamma | 122 | 28.7% |
| gamma | 344 | 26.6% |
| gamma | 779 | 13.0% |
| gamma | 964 | 14.6% |
| gamma | 1,090 | 10.2% |
| gamma | 1,110 | 13.7% |
| gamma | 1,410 | 21.1% |

- Bioassay method: whole body counting

**Europium-155**

- Production years: 1955–1957, 1959–1968, 1975
- Half-life: 4.76 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 39.2 | 46.7% |
| beta | 44.6 | 24.8% |
| beta | 70.2 | 17.5% |
| I.C. | 36.2 | 11.1% |
| X-ray | 43.1 | 11.8% |
| gamma | 86.5 | 30.7% |
| gamma | 105 | 21.2% |

- Bioassay method: whole body counting

**Fermium-255**

- Production years: 1984, 1988
- Half-life: 20.07 hr
- Decay mode: α
- Progeny: Cf-251

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 7,020 | 92.5% |
| A.E. | 11.4 | 36.2% |
| A.E. | 15.4 | 19.4% |
| I.C. | 17.9 | 16.0% |
| I.C. | 19.7 | 31.2% |
| I.C. | 24.8 | 11.6% |
| I.C. | 32.4 | 20.4% |
| I.C. | 56.2 | 20.1% |
| I.C. | 61.5 | 13.5% |
| X-ray | 15.7 | 30.1% |
| X-ray | 20.7 | 15.2% |

- Bioassay method: transplutonium (TP0)

**Fermium-257**

- Production years: 1968–1977, 1980, 1984, 1986, 1988
- Half-life: 100.5 d
- Decay mode: α
- Progeny: Cf-253
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 6,520 | 92.4% |
| A.E. | 11.8 | 34.5% |
| A.E. | 15.8 | 18.5% |
| I.C. | 35.6 | 34.9% |
| I.C. | 36.4 | 12.8% |
| I.C. | 43.8 | 40.8% |
| I.C. | 56.5 | 14.0% |
| I.C. | 105 | 14.7% |
| X-ray | 15.7 | 25.6% |
| X-ray | 20.7 | 14.9% |
| X-ray | 110 | 16.4% |
| X-ray | 116 | 25.3% |
| gamma | 241 | 11.0% |

- Bioassay method: transplutonium (TP0)

**Gadolinium-148**

- Production years: 1970
- Half-life: 74.6 yr
- Decay mode: α

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 3,180 | 100% |

- Bioassay method: gross alpha (GA0)

**Gadolinium-153**

- Production years: 1971, 1973–1988
- Half-life: 240.4 d
- Decay mode: EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 21.1 | 11.0% |
| I.C. | 54.6 | 30.8% |
| X-ray | 40.9 | 35.0% |
| X-ray | 41.6 | 63.1% |
| X-ray | 47.1 | 12.3% |
| gamma | 97.4 | 29.0% |
| gamma | 103 | 21.1% |

- Bioassay method: rare earth (FU0) then whole body counting

**Gallium-68**

- Production years: 1971
- Half-life: 67.71 min
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 836 | 87.7% |
| gamma | 511 | 178.0% |

- Bioassay method: whole body counting

**Gallium-72**

- Production years: 1955, 1957, 1960–1970

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 14.1 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 22.1 | 15.0% |
| beta | 22.7 | 21.7% |
| beta | 346 | 27.6% |
| beta | 1,360 | 10.3% |
| gamma | 630 | 24.8% |
| gamma | 834 | 95.6% |
| gamma | 2,200 | 25.9% |
| gamma | 2,510 | 12.8% |

- Bioassay method: gross beta (013 and GB0)

**Gold-198**

- Production years: 1955, 1957–1966
- Half-life: 2.7 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 314 | 99.0% |
| gamma | 412 | 95.6% |

- Bioassay method: gross beta (013 and GB0)

**Gold-199**

- Production years: 1955, 1957, 1959–1967
- Half-life: 3.14 d
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 67.2 | 21.5% |
| beta | 82.3 | 72.0% |
| I.C. | 144 | 10.1% |
| gamma | 158 | 40.0% |

- Bioassay method: gross beta (013) then whole body counting

**Hafnium-181**

- Production years: most years between 1955, 1957, 1959–1977, 1979–1980
- Half-life: 42.4 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 121 | 92.5% |
| I.C. | 65.5 | 21.2% |
| I.C. | 122 | 12.7% |
| I.C. | 123 | 10.5% |
| X-ray | 57.7 | 16.0% |
| gamma | 133 | 43.3% |
| gamma | 346 | 15.1% |
| gamma | 482 | 80.5% |

- Bioassay method: gross beta (013 and GB0) then whole body counting

**Holmium-156**

- Production years: 1965
- Half-life: 56 min
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 83.9 | 24.1% |
| gamma | 138 | 51.1% |
| gamma | 266 | 64.9% |
| gamma | 366 | 14.3% |
| gamma | 511 | 86.3% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: rare earth (FU0)

**Holmium-166**

- Production years: 1968
- Half-life: 26.83 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 651 | 48.7% |
| beta | 694 | 50.0% |
| I.C. | 23.0 | 11.0% |
| I.C. | 71.3 | 12.7% |
| I.C. | 72.2 | 13.1% |

- Bioassay method: 013 gross beta

**Hydrogen-3**

- Production years: 1955–1957, 1959–1988
- Half-life: 12.35 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 5.7 | 100% |

- Bioassay method: HY3

**Indium-111**

- Production years: 1969–1971, 1973
- Half-life: 2.83 d
- Decay mode: EC
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 19.3 | 10.6% |
| X-ray | 23.0 | 24.0% |
| X-ray | 23.2 | 45.0% |
| gamma | 171 | 90.7% |
| gamma | 24.5 | 94.1% |

- Bioassay method: whole body counting

**Indium-114**

- Production years: 1955–1957, 1959–1977, 1981
- Half Life: 71.9 s
- Decay mode: β-, EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 779 | 99.4% |

- Bioassay method: gross beta (013)

**Indium-114m**

- Production years: 1975
- Half-life: 49.51 d
- Decay mode: EC, IT
- Progeny: In-114
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 162 | 39.8% |
| I.C. | 186 | 16.0% |
| I.C. | 187 | 12.8% |
| X-ray | 24.2 | 18.3% |
| gamma | 190 | 15.56% |

- Bioassay method: whole body counter

**Iodine-123**

- Production years: 1965, 1967–1970

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 13.3 hr
- Decay mode: EC
- Progeny: Te-123m, Te-123
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 12.7 | 13.7% |
| X-ray | 27.2 | 25.0% |
| X-ray | 27.5 | 46.5% |
| gamma | 159 | 83.3% |

- Bioassay method: thyroid count

**Iodine-132**

- Production years: 1967–1972
- Half-life: 2.3 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 242 | 12.9% |
| beta | 422 | 18.7% |
| beta | 608 | 12.5% |
| beta | 841 | 18.9% |
| gamma | 523 | 16.0% |
| gamma | 630 | 13.3% |
| gamma | 668 | 98.7% |
| gamma | 773 | 75.6% |
| gamma | 955 | 17.6% |

- Bioassay method: thyroid count

**Iridium-192**

- Production years: 1955–1968, 1970–1971, 1973–1988
- Half-life: 73.8 d
- Decay mode: β-, EC
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 162 | 41.4% |
| beta | 210 | 48.0% |
| gamma | 296 | 28.7% |
| gamma | 308 | 29.7% |
| gamma | 317 | 82.7% |
| gamma | 468 | 47.8% |

- Bioassay method: gross beta (013) then whole body counting

**Iridium-194**

- Production years: 1959, 1961, 1963, 1968
- Half-life: 19.3 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 846 | 85.4% |
| gamma | 328 | 13.1% |

- Bioassay method: gross beta (013) then whole body counting

**Iron-59**

- Production years: 1955–1956, 1958–1967
- Half-life: 44.5 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 81 | 45.3% |
| beta | 149 | 53.1% |
| gamma | 1,100 | 56.5% |
| gamma | 1,290 | 43.2% |

- Bioassay method: gross beta (013 and GB0) then whole body counting, Fe-59 specific method (009) used between 1960 and 1964

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Krypton-85**

- Production years: 1955–1988
- Half-life: 10.76 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions: NA

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 252 | 99.6% |
| gamma | 514 | 0.4% |

- Bioassay method: NA-noble gas: external monitoring is controlling for these materials

**Lanthanum-140**

- Production years: 1955–1957, 1959–1966, 1987
- Half-life: 1.68 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 442 | 11.2% |
| beta | 488 | 45.2% |
| beta | 630 | 19.7% |
| gamma | 329 | 20.3% |
| gamma | 487 | 45.5% |
| gamma | 816 | 23.3% |
| gamma | 1,600 | 95.4% |

- Bioassay method: rare earth (FU0) and whole body counting

**Lead-203**

- Production years: 1972–1973
- Half-life: 51.9 hr
- Decay mode: EC
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 10.1 | 17.6% |
| I.C. | 193 | 13.6% |
| X-ray | 71.1 | 25.8% |
| X-ray | 73.1 | 43.5% |
| gamma | 279 | 80.8% |

- Bioassay method: whole body counting

**Magnesium-28**

- Production years: 1966, 1969–1970, 1977, 1983–1984, 1987–1988
- Half-life: 20.91 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 156 | 94.7% |
| I.C. | 29.1 | 27.7% |
| gamma | 401 | 36.6% |
| gamma | 941 | 38.3% |
| gamma | 1,340 | 52.6% |

- Bioassay method: whole body counting

**Manganese-52**

- Production years: 1960
- Half-life: 5.59 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 242 | 29.7% |
| gamma | 511 | 59.3% |
| gamma | 744 | 90.0% |
| gamma | 936 | 94.5% |
| gamma | 1,430 | 100.0% |

- Bioassay method: gross beta (013)

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Mercury-203**

- Production years: 1955–1957, 1959–1967
- Half-life: 46.6 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 57.8 | 100.0% |
| I.C. | 193 | 13.8% |
| gamma | 279 | 81.5% |

- Bioassay method: gross beta (013) then whole body counting

**Molybdenum-99**

- Production years: 1957, 1959–1971
- Half-life: 65.9 hr
- Decay mode: β-
- Progeny: Tc-99m, Tc-99
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 133 | 16.4% |
| beta | 443 | 82.2% |
| gamma | 740 | 12.13% |

- Bioassay method: gross beta (013) then whole body counting

**Neodymium-140**

- Production years: 1969
- Half-life: 3.37 d
- Decay mode: EC
- Progeny: Pr-140

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions: emissions listed include Pr-140 progeny

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| X-ray | 35.6 | 21.7% |
| X-ray | 36.1 | 39.7% |
| Positron | 1,070 | 51.0% |

- Bioassay method: gross beta

**Neodymium-147**

- Production years: 1955–1957, 1959–1973, 1979
- Half-life: 10.98 d
- Decay mode: β-
- Progeny: Pm-147
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 106 | 15.3% |
| beta | 264 | 80.9% |
| I.C. | 45.9 | 49.2% |
| X-ray | 38.2 | 13.3% |
| X-ray | 38.8 | 24.1% |
| gamma | 91.1 | 27.9% |
| gamma | 531 | 13.1% |

- Bioassay method: rare earth (FU0)

**Neodymium-149**

- Production years: 1979
- Half-life: 1.73 hr
- Decay mode: β-
- Progeny: Pm-149

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 355 | 18.6% |
| beta | 403 | 21.0% |
| beta | 515 | 17.1% |
| beta | 541 | 24.1% |
| I.C. | 69.1 | 17.6% |
| X-ray | 38.8 | 16.9% |
| gamma | 114 | 19.2% |
| gamma | 211 | 25.9% |
| gamma | 270 | 10.7% |

- Bioassay method: rare earth (FU0)

**Neptunium-236**

- Production years: 1965
- Half-life: 154,000 yr
- Decay mode: EC, β-
- Progeny: Pu-236, U-236
- Important energy emissions: annihilation photons

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 46.4 | 12.0% |
| A.E. | 103 | 71.7% |
| A.E. | 13.6 | 36.5% |
| I.C. | 83.2 | 34.4% |
| I.C. | 139 | 22.0% |
| X-ray | 13.6 | 42.7% |
| X-ray | 17.3 | 40.8% |
| X-ray | 95.1 | 20.2% |
| X-ray | 98.9 | 32.3% |
| gamma | 160 | 31.5% |

- Bioassay method: whole body counting

**Neptunium-237**

- Production years: 1955–1957, 1959, 1961–1962, 1964–1965, 1967–1968, 1970, 1972–1987
- Half-life: 2.144 E6 yr
- Decay mode: α
- Progeny: Pa-233

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,770 | 25.7% |
| alpha | 4,790 | 48.3% |
| I.C. | 36.7 | 27.3% |
| I.C. | 40.4 | 22.9% |
| I.C. | 52.9 | 14.1% |
| gamma | 29.4 | 15.0% |
| gamma | 86.5 | 12.4% |

- Bioassay method: gross alpha (GU0) and neptunium (NP0), Np-237 (017)

**Neptunium-238**

- Production years: 1965–1966
- Half-life: 2.117 d
- Decay mode: β-
- Progeny: Pu-238
- Important energy emissions: annihilation photons

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 72.2 | 44.8% |
| beta | 412 | 41.0% |
| I.C. | 21.7 | 30.9% |
| I.C. | 26.0 | 26.5% |
| I.C. | 39.5 | 16.3% |
| gamma | 984 | 25.2% |
| gamma | 1,030 | 18.3% |

- Bioassay method: gross beta (013 and GB0)

**Nickel-63**

- Production years: most years 1955–1957, 1959–1972, 1978, 1980, 1985–1987
- Half-life: 100.1 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 17.4 | 100% |

- Bioassay method: gross beta (013 and GB0)

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Nickel-66**

- Production years: 1968
- Half-life: 54.6 hr
- Decay mode: β-
- Progeny: Cu-66
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 73.4 | 100% |

- Bioassay method: gross beta (GB0)

**Niobium-90**

- Production years: 1957
- Half-life: 14.6 hr
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 662 | 53.7% |
| I.C. | 123 | 18.0% |
| gamma | 511 | 107.0% |
| gamma | 1,130 | 92.7% |
| gamma | 2,320 | 82.0% |

- Bioassay method: gross beta (013)

**Niobium-92**

- Production years: 1963
- Half-life: 3.47 E+7 yr
- Decay mode: EC
- Progeny: stable
- Important energy emissions: annihilation photons

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.G. | 13.3 | 16.4% |
| gamma | 561 | 100.0% |
| gamma | 935 | 100.0% |

- Bioassay method: whole body counting

**Niobium-92m**

- Production years: 1967
- Half-life: 10.15 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 13.3 | 17.1% |
| gamma | 934 | 99.1% |

- Bioassay method: whole body counting

**Niobium-95**

- Production years: 1955–1957, 1959–1981, 1983–1985
- Half-life: 35 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 43.4 | 100.0% |
| gamma | 766 | 99.8% |

- Bioassay method: gross beta (013), Nb-95 specific method (005 – Zn/Nb95), whole body counting

**Osmium-191**

- Production years: 1957, 1959–1970, 1984
- Half-life: 15.4 d
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 37.8 | 100.0% |
| I.C. | 53.1 | 65.3% |
| X-ray | 63.5 | 18.2% |
| X-ray | 65.1 | 31.3% |
| gamma | 129.42 | 29.0% |

- Bioassay method: gross beta (013) and whole body counting

**Palladium-109**

- Production years: 1957, 1959–1971
- Half-life: 13.7 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 361 | 99.9% |
| I.C. | 62.6 | 41.1% |
| I.C. | 84.5 | 19.3% |
| I.C. | 84.7 | 22.4% |
| X-ray | 22.1 | 18.6% |

- Bioassay method: gross beta (013 and GB0)

**Phosphorus-32**

- Production years: 1955–1967
- Half-life: 14.26 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 695 | 100% |

- Bioassay method: P-32 specific method (PH2)

**Phosphorus-33**

- Production years: 1964–1965, 1967–1987

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 25.3 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 76.4 | 100 |

- Bioassay method: gross beta (013 and GB0)

**Platinum-195m**

- Production years: 1972–1974, 1978
- Half-life: 4.02 d
- Decay mode: IT
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 116 | 17.5% |
| I.C. | 118 | 40.1% |
| I.C. | 127 | 19.6% |
| X-ray | 65.3 | 22.7% |
| X-ray | 67.0 | 38.8% |
| gamma | 98.85 | 11.4% |

- Bioassay method: whole body counting

**Platinum-197**

- Production years: 1965
- Half-life: 19.89 hr
- Decay mode: β-
- Progeny: stable

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 198 | 81.2% |
| beta | 225 | 10.6% |
| I.C. | 63.0 | 30.7% |
| I.C. | 63.6 | 14.1% |
| I.C. | 65.4 | 10.5% |
| I.C. | 74.6 | 13.5% |
| gamma | 77.4 | 17.0% |

- Bioassay method: whole body scan

**Plutonium-236**

- Production years: 1968, 1970, 1973, 1975, 1981, 1984, 1986
- Half-life: 2.86 yr
- Decay mode: SF, α
- Progeny: U-232
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,720 | 30.6% |
| alpha | 5,770 | 69.3% |
| I.C. | 26.5 | 11.9% |
| I.C. | 30.4 | 10.4% |

- Bioassay method: plutonium (PU0)

**Plutonium-237**

- Production years: 1984, 1986
- Half-life: 45.2 d
- Decay mode: α, EC
- Progeny: U-233, Np-237
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 10.4 | 28.3% |
| A.E. | 13.9 | 14.6% |
| X-ray | 97.5 | 12.4% |
| X-ray | 102 | 19.8% |

- Bioassay method: plutonium (PU0)

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Plutonium-238**

- Production years: 1961–1963, 1965, 1968–1985, 1987–1988
- Half-life: 87.7 yr
- Decay mode: SF, α
- Progeny: U-234, Np-237
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,460 | 29.0% |
| alpha | 5,500 | 70.9% |
| I.C. | 22.5 | 10.9% |

- Bioassay method: gross alpha (GU0), plutonium (PU0)

**Plutonium-239**

- Production years: 1955–1956, 1961–1972, 1974–1985, 1987–1988
- Half-life: 2.4E4 yr
- Decay mode: α
- Progeny: U-235
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,110 | 11.9% |
| alpha | 5,140 | 17.1% |
| alpha | 5,160 | 70.7% |

- Bioassay method: gross alpha (GU0), Pu-239 specific method (PU9), plutonium (PU0)

**Plutonium-240**

- Production years: 1961–1966, 1968–1986, 1988
- Half-life: 6,564 yr
- Decay mode: SF, α
- Progeny: U-236
- Important energy emissions:

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,120 | 27.1% |
| alpha | 5,170 | 72.8% |
| I.C. | 24.2 | 10.3% |

- Bioassay method: gross alpha (GU0) and plutonium (PU0)

**Plutonium-242**

- Production years: 1961–1988
- Half-life: 3.75E+05 yr
- Decay mode: SF, α
- Progeny: U-238
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,860 | 23.5% |
| alpha | 4,900 | 76.5% |

- Bioassay method: gross alpha (GU0) and plutonium (PU0)

**Plutonium-244**

- Production years: 1968, 1970–1982
- Half-life: 8.00 E7 yr
- Decay mode: SF, α
- Progeny: U-240
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,550 | 19.4% |
| alpha | 4,590 | 80.5% |

- Bioassay method: plutonium (PU0)

**Polonium-210**

- Production years: 1962, 1966
- Production method: β: Bi-210, EC: At-210, α: Rn-214
- Half-life: 138.4 d
- Decay mode: α

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,300 | 100% |

- Bioassay method: gross alpha (GU0)

**Potassium-40**

- Production years: 1979
- Half-life: 1.25E9 yr
- Decay mode: β-, EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 585 | 89.1% |
| gamma | 1,460 | 10.7% |

- Bioassay method: whole body counting

**Potassium-42**

- Production years: 1955–1966
- Half-life: 12.36 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 824 | 17.6% |
| beta | 1,570 | 81.9% |
| gamma | 1,520 | 18.1% |

- Bioassay method: gross beta (013) then whole body counting

**Potassium-43**

- Production years: 1964–1965, 1967, 1971, 1973–1978, 1980–1981, 1983
- Half-life: 22.3 hr
- Decay mode: β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 297 | 90.9% |
| gamma | 373 | 86.8% |
| gamma | 617 | 79.2% |

- Bioassay method: whole body counting

**Praseodymium-142**

- Production years: 1956–1957, 1959–1968, 1970
- Half-life: 19.12 hr
- Decay mode: β-, EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 834 | 96.3% |
| gamma | 1,580 | 3.68% |

- Bioassay method: rare earth (FU0)

**Praseodymium-143**

- Production years: 1955–1957, 1959–1968, 1970, 1972–1973
- Half-life: 13.57 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 315 | 100% |

- Bioassay method: rare earth (FU0)

**Praseodymium-144**

- Production years: 1962
- Half-life: 17.28 min
- Decay mode: β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 1,220 | 97.9% |

- Bioassay method: rare earth (FU0)

**Promethium-146**

- Production years: 1974
- Half-life: 5.53 yr
- Decay mode: β-, EC
- Progeny: Sm-146
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 260 | 31.9% |
| gamma | 454 | 65.0% |
| gamma | 736 | 22.5% |
| gamma | 747 | 34.0% |

- Bioassay method: rare earth (FU0), whole body counting

**Promethium-147**

- Production years: 1955–1968, 1970–1987
- Half-life: 2.46 yr
- Decay mode: β-
- Progeny: Sm-147
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 61.9 | 100% |

- Bioassay method: rare earth (FU0), Pm-147 specific method (PM7) used in 1987

**Promethium-148**

- Production years: 1970
- Half-life: 5.37 d
- Decay mode: β-

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 341 | 33.3% |
| beta | 976 | 55.5% |
| gamma | 550 | 22.0% |
| gamma | 915 | 11.5% |
| gamma | 1,470 | 22.2% |

- Bioassay method: rare earth (FU0), whole body counting

**Protactinium-231**

- Production years: 1961–1963, 1965–1966, 1968–1969, 1976–1981, 1984–1986
- Half-life: 3.28E4 yr
- Decay mode: α
- Progeny: Ac-227
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,950 | 23.0% |
| alpha | 5,020 | 25.6% |
| alpha | 5,030 | 20.2% |
| alpha | 5,060 | 11.1% |

- Bioassay method: protactinium (PA0) and Pa231/233 fecal (PF3)

**Protactinium-233**

- Production years: 1963–1964, 1966, 1969
- Half-life: 26.97 d
- Decay mode: β-
- Progeny: U-233
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 41.4 | 25.4% |
| beta | 46.3 | 15.0% |
| beta | 62.9 | 36.7% |
| beta | 71.3 | 15.6% |
| I.C. | 196 | 29.7% |
| gamma | 312 | 38.6% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: Pa-233 beta (PA3), whole body counting

**Rhenium-186**

- Production years: 1957, 1959–1972, 1979
- Half-life: 90.46 hr
- Decay mode: β-, EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 306 | 21.5% |
| beta | 359 | 70.9% |

- Bioassay method: gross beta (013)

**Rhodium-102**

- Production years: 1958
- Half-life: 207 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 413 | 20.0% |
| positron | 576 | 11.3% |
| gamma | 475 | 45.9% |
| gamma | 511 | 30.8% |

- Bioassay method: gross beta (013), whole body counting

**Rubidium-83**

- Production years: 1969
- Half-life: 86.2 d
- Decay mode: EC
- Progeny: Kr-83m

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 10.8 | 23.4% |
| gamma | 520 | 44.7% |
| gamma | 530 | 29.3% |
| gamma | 553 | 16.0% |

- Bioassay method: whole body counting

**Rubidium-84**

- Production years: 1964–1965, 1969, 1975
- Half-life: 32.77 d
- Decay mode: EC, β+, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 339 | 14.0% |
| positron | 75.7 | 13.1% |
| A.E. | 10.8 | 16.3% |
| gamma | 511 | 54.2% |
| gamma | 882 | 69.0% |

- Bioassay method: whole body counting

**Rubidium-86**

- Production years: 1955–1957, 1959–1972
- Half-life: 18.64 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 70.9 | 91.4% |
| gamma | 1,080 | 9.0% |

- Bioassay method: gross beta (013) then whole body counting

**Rubidium-88**

- Production years: 1964

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Half-life: 17.78 min
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 2,370 | 78.0% |
| gamma | 898 | 14.0% |
| gamma | 1,840 | 21.4% |

- Bioassay method: whole body counting

**Ruthenium-97**

- Production years: 1959–1960, 1962, 1970
- Half-life: 2.9 d
- Decay mode: EC
- Progeny: Tc-97m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 15.4 | 14.0% |

- Bioassay method: gross beta (013)

**Ruthenium-105**

- Production years: 1956
- Half-life: 4.44 hr
- Decay mode: β-
- Progeny: Rh-105
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 397 | 18.8% |
| beta | 405 | 16.9% |
| beta | 431 | 47.8% |
| I.C. | 107 | 14.4% |
| gamma | 469 | 17.5% |
| gamma | 676 | 15.7% |
| gamma | 724 | 47.3% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: gross beta (013)

**Ruthenium-106**

- Production years: 1955–1957, 1959–1988
- Half-life: 373.6 d
- Decay mode: β-
- Progeny: Rh-106
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 10.0 | 100% |

- Bioassay method: Ru-106 specific method (RU6)

**Samarium-151**

- Production years: 1968–1982, 1984–1987
- Half-life: 90 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 19.8 | 99.1% |

- Bioassay method: rare earth (FU0)

**Samarium-153**

- Production years: 1956–1957, 1959–1961, 1963–1969
- Half-life: 46.7 hr
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 200 | 32.2% |
| beta | 225 | 49.6% |
| beta | 264 | 17.5% |
| I.C. | 21.1 | 22.1% |
| I.C. | 54.6 | 43.4% |
| X-ray | 40.9 | 17.9% |
| X-ray | 41.6 | 32.2% |
| gamma | 103 | 29.8% |

- Bioassay method: rare earth (FU0)

**Scandium-46**

- Production years: 1955–1957, 1959–1973
- Half-life: 83.8 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 112 | 100% |
| gamma | 889 | 100% |
| gamma | 1,120 | 100% |

- Bioassay method: rare earth (FU0)

**Scandium-49**

- Production years: 1955, 1965
- Half-life: 57.2 min
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 818 | 99.9% |

- Bioassay method: rare earth (FU0)

**Silver-110m**

- Production years: 1955–1957, 1959–1966

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 249.76 d
- Decay mode: IT, β-
- Progeny: Ag-110
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 21.6 | 66.9% |
| beta | 165 | 30.1% |
| gamma | 658 | 94.3% |
| gamma | 885 | 72.7% |
| gamma | 937 | 34.2% |
| gamma | 1,380 | 24.9% |

- Bioassay method: gross beta (013 and GB0)

**Silver-111**

- Production years: 1956–1957, 1959–1970
- Half-life: 7.45 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 364 | 91.7% |

- Bioassay method: gross beta (013)

**Sodium-22**

- Production years: 1955–1956, 1961–1964
- Half-life: 2.6 yr
- Decay mode: EC, β+
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 215 | 89.8% |
| gamma | 511 | 180.0% |
| gamma | 1,270 | 99.9% |

- Bioassay method: gross beta (013), whole body counting

**Sodium-24**

- Production years: 1955–1967
- Half-life: 14.96 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 554 | 99.9% |
| gamma | 1,370 | 100.0% |
| gamma | 2,750 | 99.9% |

- Bioassay method: gross beta (013), Na-24 specific method used in 1960, whole body counting

**Strontium-82**

- Production years: 1970
- Half-life: 25.36 d
- Decay mode: EC
- Progeny: Rb-82
- Important energy emissions: emissions listed from Rb-82 progeny

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| Gamma | 776 | 13% |
| Positron | 1,520 | 83% |

- Bioassay method: whole body counting

**Strontium-89**

- Production years: 1955–1957, 1959–1963, 1965–1987
- Half-life: 50.5 d
- Decay mode: β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 585 | 100% |

- Bioassay method: strontium (SR0), Sr-89 specific urine method (SR9) beginning in 1960

**Strontium-90**

- Production years: 1955–1988
- Half-life: 28.79 yr
- Decay mode: β-
- Progeny: Y-90
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 196 | 100% |
| beta[a] | 933 | 100% |

a. See Comments below.

- Bioassay method: strontium (SR0)

**Sulfur-35**

- Production years: 1955–1969
- Half-life: 87.5 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 48.7 | 100% |

- Bioassay method: S-35 specific method (001)

**Tantalum-182**

- Production years: 1955–1957, 1959–1972, 1974
- Half-life: 114.43 d
- Decay mode: β-

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 73.2 | 29.5% |
| beta | 129 | 20.7% |
| beta | 158 | 40.0% |
| I.C. | 88.5 | 16.6% |
| I.C. | 89.9 | 14.9% |
| gamma | 1,120 | 34.9% |
| gamma | 1,190 | 16.2% |
| gamma | 1,220 | 27.0% |
| gamma | 1,230 | 11.4% |

- Bioassay method: gross beta (013) then whole body counting

**Technetium-95m**

- Production years: 1957–1958, 1967, 1970
- Half-life: 61 d
- Decay mode: EC, β+, IT
- Progeny: Tc-95
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 14.7 | 14.5% |
| gamma | 204 | 63.2% |
| gamma | 582 | 30.0% |
| gamma | 835 | 26.6% |

- Bioassay method: gross beta (013) then whole body counting

**Technetium-99**

- Production years: 1955–1957, 1959–1970, 1972–1988
- Half-life: 2.11E5 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 101 | 100% |

- Bioassay method: gross beta (013, GB0), Tc-99 specific method (006) beginning in 1960

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Technetium-99m**

- Production years: 1966, 1968, 1970
- Half-life: 6.02 hr
- Decay mode: IT
- Progeny: Tc-99
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| gamma | 141 | 89.1% |

- Bioassay method: whole body counting

**Tellurium-132**

- Production years: 1963, 1968
- Half-life: 3.204 d
- Decay mode: β-
- Progeny: I-132
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 67.0 | 100.0% |
| I.C. | 16.6 | 74.0% |
| gamma | 228 | 88.0% |

- Bioassay method: whole body counting

**Terbium-158**

- Production years: 1970
- Half-life: 180 yr
- Decay mode: β-, EC
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 275 | 15.5% |
| I.C. | 29.2 | 23.2% |
| I.C. | 71.6 | 16.2% |
| I.C. | 72.3 | 17.6% |
| gamma | 944 | 43.9% |
| gamma | 962 | 20.3% |

- Bioassay method: rare earth (FU0)

**Thallium-201**

- Production years: unknown quantity in 1975
- Half-life: 72.9 hr
- Decay mode: EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 84.1 | 15.6% |
| X-ray | 69.1 | 27.4% |
| X-ray | 71.1 | 46.4% |
| gamma | 167 | 10.0% |

- Bioassay method: whole body counting

**Thallium-204**

- Production years: 1955–1971
- Half-life: 3.78 yr
- Decay mode: EC, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 244 | 97.1% |

- Bioassay method: gross beta (013 and GB0)

**Thorium-228**

- Production years: 1962

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Half-life: 1.91 yr
- Decay mode: α
- Progeny: Ra-224
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,340 | 27.2% |
| alpha | 5,420 | 72.1% |
| I.C. | 65.8 | 10.7% |

- Bioassay method: gross alpha (GU0)

**Thorium-229**

- Production years: 1968, 1970–1971, 1973–1974, 1977, 1979–1986, 1988
- Half-life: 7340 yr
- Decay mode: α
- Progeny: Ra-225
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,850 | 55.6% |
| alpha | 4,900 | 10.1% |
| X-ray | 85.8 | 15.3% |
| X-ray | 88.9 | 25.1% |

- Bioassay method: gross alpha and fecal monitoring (GF0, TF0)

**Thorium-230**

- Production years: 1956, 1962–1963, 1965, 1967–1976, 1978–1988
- Half-life: 75,380 yr
- Decay mode: α
- Progeny: Ra-226
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,620 | 23.4% |
| alpha | 4,690 | 76.4% |

- Bioassay method: gross alpha and fecal monitoring (GF0, TF0), Th-230

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Thorium-232**

- Production years: 1963, 1968–1969, 1972–1976, 1978–1987
- Half-life: 1.4E10 yr
- Decay mode: α
- Progeny: Ra-228
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 3,950 | 21.7% |
| alpha | 4,010 | 78.2% |

- Bioassay method: gross alpha and fecal monitoring, (GF0, TF0)

**Thorium-234**

- Production years: 1981
- Half-life: 24.1 d
- Decay mode: β-
- Progeny: Pa-234m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 26.7 | 19.2% |
| beta | 52.4 | 70.3% |
| I.C. | 71.3 | 10.8% |

- Bioassay method: gross beta (GB0)

**Thulium-170**

- Production years: 1962–1971, 1974–1975
- Half-life: 128.6 d
- Decay mode: EC, β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 290 | 18.3% |
| beta | 323 | 81.6% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: rare earth (FU0)

**Thulium-171**

- Production years: 1967
- Half-life: 1.92 yr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 25.1 | 98% |

- Bioassay method: rare earth (FU0)

**Tin-117m**

- Production years: 1977
- Half-life: 13.76 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 127 | 66.3% |
| I.C. | 152 | 13.7% |
| I.C. | 152 | 10.6% |
| gamma | 159 | 86.4% |

- Bioassay method: whole body counting

**Titanium-44**

- Production years: 1956, 1958
- Half-life: 60 yr
- Decay mode: EC
- Progeny: Sc-44

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| gamma | 67.9 | 93.0% |
| gamma | 78.4 | 96.4% |

- Bioassay method: gross beta (013), radiation from daughter Sc-44

**Tungsten-185**

- Production years: 1955–1957, 1959–1971
- Half-life: 75.1 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 127 | 99.9% |

- Bioassay method: gross beta (013 and GB0)

**Tungsten-187**

- Production years: 1955–1957, 1959–1970
- Half-life: 23.7 hr
- Decay mode: β-
- Progeny: Re-187
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 193 | 55.4% |
| beta | 457 | 30.1% |
| I.C. | 62.4 | 16.7% |
| gamma | 480 | 21.8% |
| gamma | 686 | 27.3% |

- Bioassay method: gross beta (013), whole body counting

**Uranium-232**

- Production years: 1961–1965, 1968, 1970–1971, 1974–1979
- Half-life: 68.9 yr
- Decay mode: α

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Progeny: Th-228
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 5,260 | 31.5% |
| alpha | 5,320 | 68.1% |
| I.C. | 38.0 | 12.1% |
| I.C. | 41.5 | 10.3% |

- Bioassay method: uranium (UR0)

**Uranium-233**

- Production years: 1961–1963, 1965–1988
- Half-life: 1.59E5 yr
- Decay mode: α
- Progeny: U-233
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,780 | 13.2% |
| alpha | 4,820 | 84.5% |

- Bioassay method: uranium (UR0)

**Uranium-234**

- Production years: 1956, 1961–1963, 1965–1988
- Half-life: 2.45E5 yr
- Decay mode: α
- Progeny: Th-230
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,720 | 28.4% |
| alpha | 4,780 | 71.4% |
| I.C. | 33.4 | 11.0% |

- Bioassay method: uranium (UR0)

**Uranium-235**

- Production years: 1955–1957, 1961–1963, 1965–1988

**ATTACHMENT B**
**SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)**

- Half-life: 7E8 yr
- Decay mode: α
- Progeny: Th-231
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,370 | 17.2% |
| alpha | 4,400 | 55.6% |
| I.C. | 15.6 | 44.2% |
| gamma | 186 | 57.2% |

- Bioassay method: uranium (UR0)

**Uranium-236**

- Production years: 1955–1956, 1961–1963, 1965–1988
- Half-life: 2.34E7 yr
- Decay mode: α
- Progeny: Th-232
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,450 | 25.9% |
| alpha | 4,490 | 73.8% |

- Bioassay method: uranium (UR0)

**Uranium-238**

- Production years: 1955–1956, 1961–1988
- Half-life: 4.47E9 yr
- Decay mode: SF, α
- Progeny: Th-234
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| alpha | 4,150 | 22.3% |
| alpha | 4,200 | 77.5% |

- Bioassay method: uranium (UR0)

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Vanadium-48**

- Production years: 1962
- Half-life: 15.97 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 290 | 49.4% |
| gamma | 511 | 100.0% |
| gamma | 984 | 100.0% |
| gamma | 1,310 | 97.5% |

- Bioassay method: whole body counting

**Xenon-127**

- Production years: 1983, 1987–1988
- Half-life: 36.34 d
- Decay mode: EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| gamma | 172 | 25.5% |
| gamma | 203 | 68.3% |
| gamma | 375 | 17.2% |

- Bioassay method: NA-noble gas: external monitoring is controlling for these materials

**Xenon-133**

- Production years: 1960–1976, 1978–1980
- Half-life: 5.24 d
- Decay mode: β-
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 101 | 99.2% |
| I.C. | 45.0 | 55.4% |
| X-ray | 31.0 | 26.6% |
| gamma | 81.0 | 36.0% |

- Bioassay method: NA-noble gas: external monitoring is controlling for these materials

**Ytterbium-169**

- Production years: 1980, 1986
- Half-life: 32 d
- Decay mode: EC
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 50.3 | 35.3% |
| I.C. | 138 | 13.1% |
| gamma | 177 | 22.2% |
| gamma | 198 | 35.8% |

- Bioassay method: whole body counting

**Yttrium-86**

- Production years: 1964, 1968
- Half-life: 14.74 hr
- Decay mode: EC, β+
- Progeny: stable

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 535 | 11.9% |
| A.E | 12.0 | 13.8% |
| gamma | 443 | 16.9% |
| gamma | 511 | 63.8% |
| gamma | 628 | 32.6% |
| gamma | 703 | 15.4% |
| gamma | 777 | 22.4% |
| gamma | 1,080 | 82.5% |
| gamma | 1,150 | 30.5% |
| gamma | 1,850 | 17.2% |
| gamma | 1,920 | 20.8% |

- Bioassay method: whole body counting

**Yttrium-88**

- Production years: 1957–1958, 1961–1963, 1965, 1974
- Half-life: 106.65 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| A.E. | 12.0 | 20.0% |
| gamma | 898 | 93.7% |
| gamma | 1,840 | 99.2% |

- Bioassay method: rare earth (FU0) and whole body counting

**Yttrium-90**

- Production years: 1956–1968, 1973, 1987–1988
- Half-life: 64 hr
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 933 | 100% |

- Bioassay method: rare earth (FU0), daughter of Sr-90.

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

**Yttrium-91**

- Production years: 1955–1957, 1959–1978
- Half-life: 58.5 d
- Decay mode: β-
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 604 | 99.7% |

- Bioassay method: rare earth (FU0)

**Zinc-65**

- Production years: 1955–1957, 1959–1966
- Half-life: 243.9 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| positron | 143 | 1.4% |
| gamma | 511 | 2.8% |
| gamma | 1,120 | 50.6% |

- Bioassay method: gross beta (013), whole body counting

**Zinc-69m**

- Production years: 1967, 1973–1974
- Half-life: 13.76 hr
- Decay mode: EC, β-
- Progeny: Zn-69
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| I.C. | 429 | 4.55% |
| beta | 321 | 100.0% |
| gamma | 439 | 94.8% |

## ATTACHMENT B
## SUMMARY OF RADIONUCLIDES REQUIRING NO FURTHER ANALYSIS (continued)

- Bioassay method: gross beta (GB0), beta emission from Zn-69 progeny

**Zirconium-95**

- Production years: 1955–1986
- Half-life: 64.0 d
- Decay modes: β-
- Progeny: Nb-95m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 110 | 54.5% |
| beta | 121 | 44.3% |
| gamma | 724 | 44.3% |
| gamma | 757 | 54.4% |

- Bioassay method: gross beta (013), Zr-95/Nd-95 (005), whole body counting

**Zirconium-97**

- Production years: 1971
- Half-life: 16.74 hr
- Decay mode: β-
- Progeny: Nb-97m
- Important energy emissions:

| Emission type | Energy (keV) | Abundance |
|---|---|---|
| beta | 757 | 88.2% |
| gamma | 743 | 93.1% |

- Bioassay method: whole body counting