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

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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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

CAM	continuous air monitor
Ci	curie
cm	centimeter
cpm	counts per minute
d	day
DAC	derived air concentration
DCF	dose conversion factor
DOE	U.S. Department of Energy
GM	Geiger-Müller
HP	health physics
hr	hour
ICRP	International Commission on Radiological Protection
in.	inch
IMBA	Integrated Modules for Bioassay Analysis
keV	kiloelectron-volt (1,000 electron-volts)
m	meter
mCi	millicurie
min	minute
mL	milliliter
MPC	maximum permissible concentration
mR	milliroentgen
mrem	millirem
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH-Division of Compensation Analysis and Support Claims Tracking System
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
pCi	picocuries
RaLa	radioactive lanthanum
s	second
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
WBC	whole-body count
yr	year
Y-12	Y-12 Plant (now Y-12 National Security Complex)
µCi	microcurie

1.0 PURPOSE

This report evaluates the internal monitoring capability of Oak Ridge National Laboratory (ORNL) for radionuclides that were produced by the Isotopes Division (termed "exotic radionuclides) and its predecessors from 1955 to 1988. The evaluation was initiated after publication of Special Exposure Cohort (SEC) evaluation report for ORNL (SEC-00189; NIOSH 2012), which left the issue on exotic radionuclides reserved. As a result of the evaluation of SEC-00189, a class was added to the SEC from the beginning of ORNL operations through July 31, 1955. The SEC evaluated isotopes of uranium, plutonium, thorium, and mixed fission products. Isotope production involved a wide array of radioactive materials (termed "exotic radionuclides"). Because of the potential challenges involved in monitoring intakes from such a wide variety of materials, the National Institute for Occupational Safety and Health (NIOSH) determined that an evaluation of the monitoring methods available at the time, and of the Isotopes Division materials, was necessary. The evaluation methodology consisted of the following steps:

- Identification of radionuclides that were produced by the Isotopes Division;
- Identification of available bioassay methodologies;
- Chronological benchmarking of the available bioassay methods against the radionuclide inventory to identify potential gaps in monitoring capability; and
- Evaluation of identified monitoring gaps to determine if dose reconstruction for these exotic radionuclides is feasible.

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. It should be noted that 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 monitoring capability of the ORNL HP program to have monitored all materials that were produced and handled by the Isotopes Division regardless of production location.

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.

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.

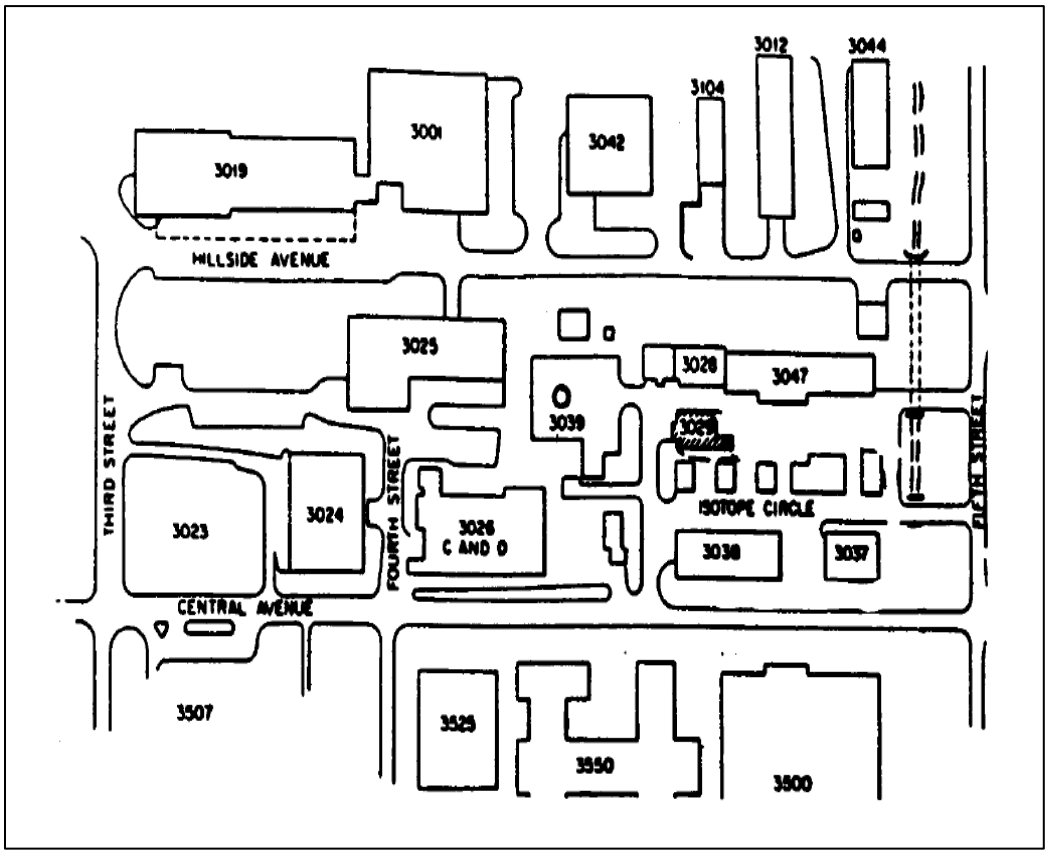

Figure 3-1. General layout of isotope facilities (Carver and Slater 1994).

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}S and ^{144}Ce, primarily for use in the Systems for the Nuclear Auxiliary Power program. Large quantities of ^{244}Cm were stored in the building (ORNL 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).

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;
- Uranium-232, -233, -234, -235, -236, -238; and
- Yttrium-78.

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.

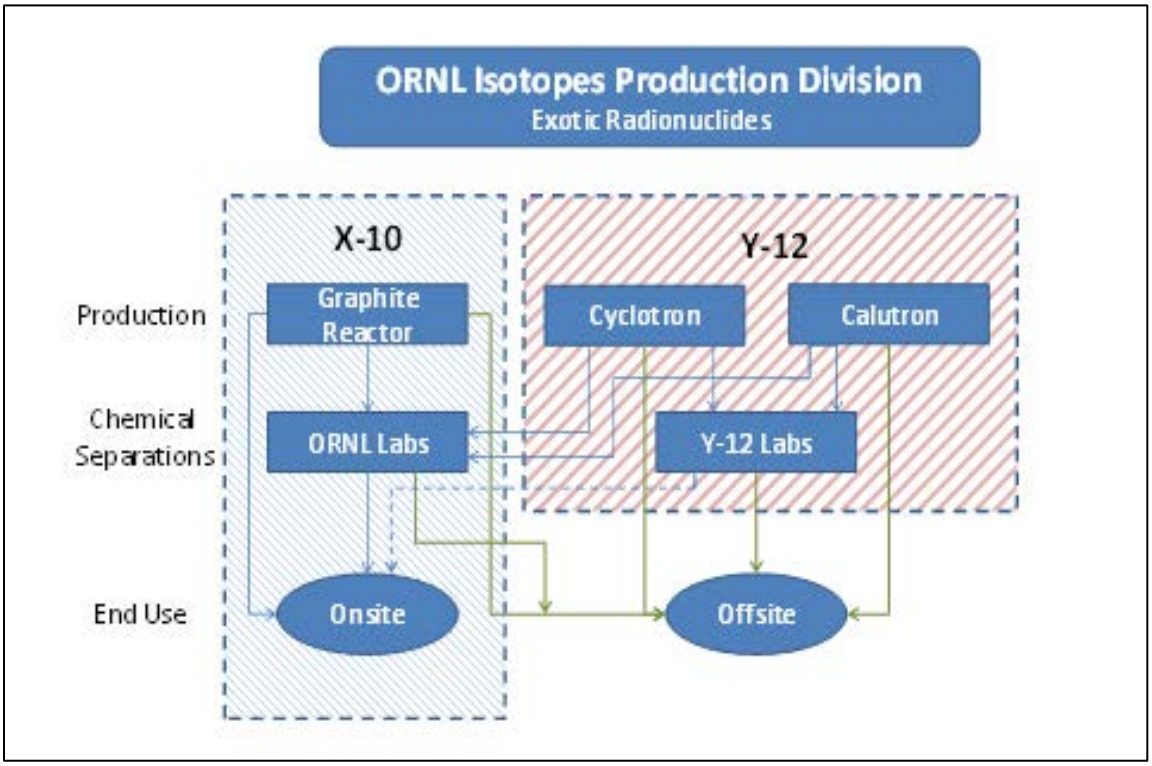

Figure 3-2. Isotope production flow, 1955 to 1965 (NIOSH 2012).

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).

In the early years of the bioassay program, 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 (ORNL 1954a) included consideration of the need to make a second request for sample submission and made use of the same request format. 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 (ORAU) Team obtained a copy of the ORNL bioassay database dated April 28, 2013 (ORNL 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

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

Bioassay code	Description/analyte	Number of samples	Period in use
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
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: 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
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

[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	Tc-99	9	1976–1979, 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

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

Year	NOCTS sample count	ORNL database sample count	N/O[a]
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 1:1.13. 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 analysis 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 analysis was 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, Snyder, and Struxness 1964).

The goal to obtain a baseline count on essentially every person with a potential for future exposure was completed in May 1965 (Morgan, Snyder, and Struxness 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, Snyder, and Struxness 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, Snyder, and Struxness 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 (whole-body and thyroid) counts taken each calendar year from the ORNL database (ORNL 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,c]
1961	0	329
1962	71	395
1963	921	1,054

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,c]
1964	1,555	1,644
1965	1,169	1,222
1966	696	740
1967	966	983
1968	968	964
1969	1,057	1,108
1970	518	530
1971	324	332
1972	259	272
1973	325	350
1974	278	278
1975	330	331[c]
1976	255	255[c]
1977	291	291[c]
1978	306	305[c]
1979	402	460[c]
1980	700	750[c]
1981	557	590[c]
1982	556	650[c]
1983	411	Not available
1984	476	Not available
1985	525	Not available
1986	682	Not available
1987	681	Not available
1988	753	Not available

a. Source data from SRDB Ref ID: 126306.
b. Source data from SRDB Ref IDs: 11555, 11558, 12061, 12066, 12069, 12072, 12084, 12087, 12092, 12093, 13224, 13226 to 13229, 13231, and 22548 to 22552.
c. 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 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 "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 (ORNL 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

Table 6-1. Sources of radionuclide production information.

Report series name	Publication frequency	Start	End	SRDB Ref IDs
Chemical Technology Division Annual Progress Report	Annual	1957	1988	103941, 104046, 109875, 118695–118698, 118701, 118706, 118708, 119232–119233, 119235, 119250, 119255, 119264, 119274–119275, 119278, 119279–119280, 119295, 119345, 120407, 120410, 120412, 120419, 120421, 120424
Electronuclear Research Division Annual Progress Report	Annual	1957	1961	11915, 11929, 11945, 121486
Isotope Separations Progress Report	Monthly	1976	1978	132481, 132490, 132493, 132495–132496, 132498, 135508, 135510, 135512–135514, 135516, 135518, 135520, 135522, 135524, 135528, 135531, 135533, 135547
Isotopes Development Center Progress Report Curium Program	Variable	1962	1964	123031, 123039, 123044, 123052, 123075, 123079, 123087, 123090, 123094
Isotopes Development Center Progress Report Fission Products	Variable	1962	1962	123030, 123060, 132911
Isotopes Development Center Progress Report Isotopes Separations	Variable	1962	1964	123036, 123053, 123059, 123078, 123083
Isotopes Development Center Progress Report Radioactive Source Development	Variable	1962	1963	123029
Isotopes Development Center Progress Report Reactor and Cyclotron Produced Isotopes	Variable	1963	1963	11934, 11941
Isotopes Development Center Progress Report Target Development	Variable	1962	1963	123035, 123047, 123058, 123077
Isotopes Division Quarterly Report	Quarterly	1960	1961	132855–132857, 132915
Isotopes Division Research and Development Report	Monthly	1962	1962	132858–132900, 132902, 132905, 132907
List of Radioisotope Customers with Summary of Radioisotope Shipments	Annual	1964	1988	40950, 56703, 76459, 77783–77784, 79142–79143, 79470–79472, 79474–79475, 87578–87579–87581, 100264, 100266, 100517–100519, 100712, 101613, 115758, 126941, 160563
ORNL Status and Progress Report	Monthly	1950	1967	102645, 120325, 120334, 120347, 120359, 120362, 120366, 120371, 120374–120376, 120378, 120380–120381, 120383–120384, 120386, 120389, 120397–120399, 120401–120403, 120405–120406, 121166–121193, 121195–121289, 121483, 121485, 122579, 122580–122583, 122585–122588, 122591–122601, 122603, 122605, 122798–122800, 122841, 122847–122848, 122851, 122853, 122859, 122861, 122863, 122866–122867, 122883, 122885, 122890–122891

Table 6-1. Sources of radionuclide production information (continued).

Report series name	Publication frequency	Start	End	SRDB Ref IDs
Quantity Data on Radioisotopes	Quarterly	1959	1964	14019, 121493, 121497, 122815 - 122817, 122819 - 122831
Radioisotope Cost-Price Study	Annual	1957	1974	101798, 122748–122751, 132204, 133608, 137545, 137558, 137577, 137586
Radioisotope Distribution Program Progress Report	Monthly	1973	1980	98043, 119487–119495, 120818–120861, 120863, 120869–120870, 120872–120873, 121291–121296, 123183, 123229, 123237, 123263, 123301, 123303, 123305, 123307
Radioisotope Inventory	Monthly	1956	1966	121516, 121538, 121640, 121644, 121646–121647, 121649, 121651, 121653, 137579
Radioisotope Production and Process Development Annual Report	Annual	1954	1956	103912, 103938, 120365
Radioisotope Program (8000) Progress Report	Monthly	1969	1973	119509, 119511–119517, 120529–120531, 120533–120565, 121856
Review of Radioisotopes Program	Annual	1964	1967	79379, 119485–119486, 122852
Stable Isotope and Heavy Element Inventories	Monthly	1961	1969	121487–121490, 121494–121495, 121498, 121500, 121502–121503, 121505, 121508, 137542, 137615, 137682, 137689–137690, 137692, 137697
Transuranium Processing Plant Semiannual Report of Production, Status, and Plan	Semi-annual	1969	1975	126245, 132271, 132286, 132288, 132300–132306, 132386

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 9.2×10^{16} years and 2.4×10^{24} years, respectively).

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

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, 25 additional radionuclides were identified, and one or more additional inventory years were identified for 23 radionuclides. Table 6-3 provides the final inventory list based on the above-listed data sources.

Table 6-3. 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
Arsenic-71	1960
Arsenic-72	1960
Arsenic-74	1957–1959, 1961, 1965
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

Table 6-3. Final radionuclide inventory for Isotopes Division (continued).

Nuclide	Production years
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
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

Table 6-3. Final radionuclide inventory for Isotopes Division (continued).

Nuclide	Production years
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	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	1958
Erbium-171	1973
Thulium-170	1962–1971, 1974–1975
Thulium-171	1967
Ytterbium-169	1980, 1986
Hafnium-181	1955, 1957, 1959–1977, 1979–1980
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

Table 6-3. Final radionuclide inventory for Isotopes Division (continued).

Nuclide	Production years
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	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	1961–1966, 1968, 1986
Curium-243	1965, 1972–1973, 1975–1976, 1981–1983
Curium-244	1962–1964, 1966–1988
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

Table 6-3. Final radionuclide inventory for Isotopes Division (continued).

Nuclide	Production years
Fermium-255	1984, 1988
Fermium-257	1968–1977, 1980, 1984, 1986, 1988

7.0 FEASIBILITY ANALYSIS

7.1 INITIAL EVALUATION

The annual production history for each of the 213 radionuclides in Table 6-3 was compared to the available in vitro bioassay methods for each year (Tables 4-1 to 4-3) 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.

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

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 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).

In the tables 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 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.

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 7-5 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 Attachment C. 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.

7.2 ADDITIONAL EVALUATION

As indicated in Table 7-4, 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). NOTE: Separate analyses have been completed for the five of the remaining six (radioiodines are provided in Attachment C). The one remaining (Pu-241) was processed and handled on the Y-12 campus and as such, not addressed further in this document.

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 1.6×10^{-5} µCi/cm^3 (^{87m}Sr) to 5.9×10^{-8} µCi/cm^3 (^{109}Cd). For comparison purposes, before publication of NBS Handbook 69 in 1961 the tolerance value for airborne beta/gamma activity in ORNL facilities was set at 1×10^{-7} µCi/cm^3. Respiratory protection was required for entry above 10% of this limit (1×10^{-8} µCi/cm^3). By 1961, the maximum permissible concentration (MPC) concept within National Bureau of

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	Y	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	(b)	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	Y	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	Y	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	Y	G	N
Yttrium-91	013/GB0; FU0	G	G	G	N	G	G	G	G	G	G	G	G	Y	G	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;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	R	R	R	R	R	R	R	R	R	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	Y	G	G
Praseodymium-142	013/GB0;FU0	N	G	G	N	G	G	G	G	G	G	G	G	Y	G	N
Praseodymium-143	013/GB0;FU0	G	G	G	N	G	G	G	G	G	G	G	G	Y	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; SC	G	G	G	N	G	G	G	G	G	G	G	G	Y	G	G
Neodymium-149	013/GB0;FU0; SC	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;PM7; FU0;Pm-147	G	G	G	G	G	G	G	G	G	G	G	G	Y	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	Y	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	G	N	N	N	N	N	N	N	N	N	N	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	Y	G	G
Thulium-171	FU0	N	N	N	N	N	N	N	N	N	N	N	N	Y	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;Th-230	N	G	N	N	N	N	N	Y	Y	N	G	N	G	G	Y
Thorium-232	GF0;TF0;	N	N	N	N	N	N	N	N	Y	N	N	N	N	G	Y
Thorium-234	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	N	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	R	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	N	N	N	N	N	N	G	G	G	G	G	G	G	G	G
Curium-242	000(Cm-242); TP0	N	N	N	N	N	N	G	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	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 vitro analysis, TH indicates monitored by in vitro 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[a]	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	Y	G	Y	Y	N	N	N	N	Y	Y	Y	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[a]	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	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[a]	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;GB0;	G	N	Y	G	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	G	G	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	G	G	G	G	G	G	G	G	G	G	G	G	G	G
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[a]	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	Y	N	Y	Y	Y	Y	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; SC	G	G	G	G	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N
Neodymium-149	013/GB0;FU0; SC	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;PM7; FU0;Pm-147	G	G	G	G	G	G	G	G	G	Y	G	Y	Y	Y	Y	G	Y	Y	N

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

Nuclide	Bioassay method code[a]	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	Y	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	G	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[a]	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	004;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	Y	Y	N	Y	Y	N	N	G	N	G	G	G	G	G	Y	Y	G	N	Y
Thorium-230	GF0;TF0;Th-230	Y	Y	G	Y	Y	G	G	N	G	G	G	G	G	G	Y	Y	G	Y	Y
Thorium-232	GF0;TF0;	N	N	G	Y	Y	G	G	N	G	G	G	G	G	G	Y	Y	G	Y	N
Thorium-234	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[a]	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.

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

Nuclide	Production years	Half life	Decay mode[a]	Photon energy[b] (keV)	Electron energy[b] (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. EC = decay by electron capture, IT = decay by isomeric transition, β– = decay by beta emission.
b. Emitted photon and X-ray energy per transformation.
c. Emitted beta, conversion electron, and auger electron energy per transformation.

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

Nuclide	DAC[a] (µCi/cm^3)
Beryllium-7	1.2E-05
Calcium-41	3.0E-06
Chromium-51	1.6E-05
Manganese-54	4.7E-07
Iron-55	6.1E-07
Cobalt-57	9.4E-07
Gallium-67	2.0E-06
Selenium-75	3.3E-07
Strontium-85	8.8E-07

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

Nuclide	DAC[a] (µCi/cm^3)
Strontium-87m	1.6E-05
Molybdenum-93	4.0E-07
Ruthenium-103	2.6E-07
Palladium-103	1.9E-06
Cadmium-109	5.9E-08
Tin-113	3.0E-07
Tin-119m	3.8E-07
Tellurium-121	1.1E-06
Cesium-131	1.3E-05
Barium-133	3.1E-07
Cerium-139	4.0E-07
Promethium-145	2.3E-07
Terbium-156	4.0E-07
Dysprosium-159	2.3E-06
Tungsten-181	1.3E-05
Osmium-185	4.0E-07
Gold-195	4.7E-07
Mercury-197	1.3E-07
Bismuth-206	2.7E-07

a. Based on contemporary (ICRP 1994) DCFs and 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 committed effective dose equivalent of 5 rem.

Standards Handbook 69 (NCRP 1959) was adopted. The MPC for occupational exposure to unidentified beta/gamma emitters was set at 1 x 10^{-9} µCi/cm^3 (Hart 1960) with trigger levels remaining at 0.1 MPC (1 × 10^{-10} µCi/cm^3) for general entry without respiratory protection (ORNL 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 × 10^{-5} of the total annual inventory was computed for the year with the maximum recorded inventory (Table 7-6). The factor 1 × 10^{-5} was selected based on the guidance in NUREG-1400, which postulates that 1 × 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 (DCF; 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 × 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 × 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%.

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 1×10^{-5} time inventory[b] (mrem)
Beryllium-7	340	1,554	Extrathoracic airways	5
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	13	19,980	Extrathoracic airways	3
Cesium-131	25	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 these radionuclides.

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; ORNL 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 or another 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 7-7. Number of bioassay samples collected for code 000 analytes by year.

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

Isotope production at ORNL involved a wide array of radioactive materials it termed exotic radionuclides. Radionuclides ORNL could not readily detect by gross alpha or beta/gamma methods presented a particular monitoring challenge. This report identifies 28 radionuclides that might present such a monitoring challenge. Evaluation of the ORNL bioassay program indicates the ability to develop specialized bioassay methods as needed to adapt to changing conditions and emergent events. While evidence has not been found for all of the 28 identified nuclides, it is clear that ORNL had the capability to develop methods as needed. In addition, the relatively low radiotoxicity of these same nuclides in comparison with a bounding potential intake (Table 7-6) lends credence to the position that a significant intake of one of these nuclides would not be credible.

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ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS

TABLE OF CONTENTS

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, Davis, and Henley 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).

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, Farabee, and Khym 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.

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.

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

The first basic procedure for rare- and alkaline-earth element urinalysis was issued in 1949 (Tompkins, Farabee, and Khym 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.

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.

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, Farabee, and Khym 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

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

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, Davis, and Henley 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).

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.

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

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, Davis, and Henley 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. 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, Davis, and Henley 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.

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

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 undated).

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%.

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, Davis, and Henley 1957).

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

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, Farabee, and Khym 1949).

A report from April 15, 1950, indicates that an analysis procedure for strontium was in use (Morgan 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 1951a). 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, Davis, and Henley 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.

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

ATTACHMENT A
SUMMARY OF IN VITRO BIOASSAY METHODS (continued)

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 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 1951b).

In January 1957, a method using tributyl phosphate in hexane was in use (Brown, Davis, and Henley 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 Radiological Toolbox. When data were not available in the radiological toolbox, data were obtained from the NuDat 2.7 dataset at the National Nuclear Data Center (NNDC 2018).

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-
- 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

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

- 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
- 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:

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

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
- 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
- Important energy emissions:

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

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

- 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
- 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

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

- 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
- 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:

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

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-
- 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%

- 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:

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

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
- 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, 1967–1991
- 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), Cf-252 specific method 1989–1992

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

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
- 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: 1945–1975, 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:

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

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
- 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: 1947
- Half-life: 37.2 min
- Decay mode: β-
- Progeny: stable
- 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 and 1976
- Half-life: 77.2 d
- Decay mode: EC, β+
- Progeny: stable
- Important energy emissions:

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

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

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%

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

- 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
- 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: 1961–1966, 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
- 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%

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

Emission type	Energy (keV)	Abundance
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
- 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)

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

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
- 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:

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

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%

- 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
- Important energy emissions:

Emission type	Energy (keV)	Abundance
alpha	6,430	93.4%
A.E.	11.5	43.9%

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

Emission type	Energy (keV)	Abundance
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
- 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

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

- 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
- 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%

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

Emission type	Energy (keV)	Abundance
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
- 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:

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

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
- 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
- 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%

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

- 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%

- Bioassay method: rare earth (FU0)

Holmium-166

- Production years: 1958
- 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%

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

- 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
- 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:

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

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
- 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
- Important energy emissions:

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

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

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%

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

- 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
- 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%

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

- 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)

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

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

- Progeny: Pr-140
- 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
- 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

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

- 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
- 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: 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%

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

Emission type	Energy (keV)	Abundance
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)

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

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

- Decay mode: EC
- Progeny: stable
- Important energy emissions: annihilation photons

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
- 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%

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

Emission type	Energy (keV)	Abundance
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
- 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

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

- 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
- 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, 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

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

- 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)

Plutonium-238
- Production years: 1961–1963, 1965, 1968–1985, and 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), and 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
- 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

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

- 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-
- 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)

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

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-
- 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, 1990
- Half-life: 2.46 yr
- Decay mode: β-
- Progeny: Sm-147
- Important energy emissions:

Emission type	Energy (keV)	Abundance
beta	61.9	100%

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

- 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-
- 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: 1950, 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%

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

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

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
- 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:

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

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: 1946, 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
- 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

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

- 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%

- 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
- Important energy emissions:

Emission type	Energy (keV)	Abundance
beta	200	32.2%
beta	225	49.6%

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

Emission type	Energy (keV)	Abundance
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
- 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%

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

- 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
- 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

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

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-
- 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-
- Progeny: stable

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

- 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

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

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

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
- 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

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

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
- 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, 1990
- Half-life: 75,380 yr
- Decay mode: α
- Progeny: Ra-226
- Important energy emissions:

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

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

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%

- Bioassay method: rare earth (FU0)

Thulium-171
- Production years: 1967
- Half-life: 1.92 yr
- Decay mode: β-

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

- 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
- 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

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

- 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
- 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:

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

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
- 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)

Vanadium-48

- Production years: 1962

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

- 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
- 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:

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

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
- 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:

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

Emission type	Energy (keV)	Abundance
beta	933	100%

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

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%

- 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

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

- 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

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

C.1 OVERVIEW

Between 1946 and 1980, the Isotopes Division at ORNL produced iodine for commercial applications. The largest quantities, ranging between 740 and 3,600 Ci/yr, were produced between 1953 and 1964. An assessment of internal exposure from these activities is complicated by limited personnel monitoring data. A coworker analysis based on thyroid monitoring between 1944 and 1954 could be used to assign internal exposure to potentially exposed individuals during the period from 1955 to 1962, when routine monitoring data for iodine are not available. The early data demonstrate the capability of workplace controls for episodic iodine releases and it is reasonable to assume that such releases would be identified during the subsequent period from 1955 to 1962. Individuals with no individual monitoring data during the period would not be expected to be routinely exposed beyond the reported levels in the earlier monitoring data, which were largely collected after the occurrence of a release or incident.

C.2 RADIOIODINE INVENTORY

Production of radioiodine at ORNL began in 1946, initially through irradiation of tellurium. By 1958, production had shifted to separation of the iodine fission product from reactor fuel (Rupp, Beauchamp, and Farmakes 1958). The production activities were initially performed in Building 3026C/D (706C/D at that time); by 1951, they had shifted to a new facility in Building 3028 (910 at that time) (Ramsey 1950). In addition, between 1944 and 1956, significant quantities of iodine were present in facilities as a byproduct of radioactive lanthanum (RaLa) production – not to be confused with the commercial iodine-production process. During this period, between 8,800 and 42,000 Ci of radioactive iodine were released annually as a RaLa byproduct (ATSDR 2008). This quantity is an order of magnitude higher than the amounts produced by the isotopes group (Table C-1).

Separations activities were primarily conducted in Buildings 706C and 706D (later 3026C/D), 3028 (Radioisotope Production Laboratory), and 3047 (Isotope Technology Building). However, radioiodine exposure was possible in any area where reactor fuel processing was performed, such as 3019 (Pilot Plant, Radiochemical Development Laboratory, High Level Radiation Analytical Laboratory), 3505 (Metal Recovery Facility), 3515 (Fission Product Semi-Works), 3517 (Fission Product Development Laboratory), and 4507 (High Level Chemical Development Laboratory) (Brooksbank, Patton, and Krichinsky 1994; ORAUT 2007).

Table C-1 shows annual production through 1969.

C.3 WORKPLACE MONITORING

Air monitoring was an integral part of the ORNL radiological monitoring program from the onset of operations. Applied HP annual reports list the total and/or average number of gross beta/gamma air samples (see Table C-2). These data were in the form of annual summaries only. Detailed information and breakdown by work area is not available in the SRDB.

Tolerance values were established by 1944 based on gross beta air concentrations and areas were evacuated at the tolerance level (1×10^{-07} µCi/cm^3). Respiratory protection was required at 10% of the tolerance air concentration (1×10^{-08} µCi/cm^3) (AEC 1947). Entry into areas with respiratory protection was allowed up 100 times tolerance (1×10^{-05} µCi/cm^3) (Sadowski 1953). The “operating maximum permissible level” was defined as 10% of the MPC and was 1×10^{-8} µCi/cm^3 during this period. By 1961, the guidance in NCRP (1959) about the concept of MPC was adopted. Therefore, the MPC for occupational exposure to unidentified beta/gamma-emitters was set at 10^{-9} µCi/cm^3 (Hart

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Table C-1. Commercial ^{131}I production, 1946 to 1969.[a]

Year	Amount (Ci)
1946	1.3
1947	10
1948	46
1949	190
1950	310
1951	450
1952	490
1953	1,700
1954	820
1955	1,000
1956	740
1957	1,200
1958	3,600
1959	2,300
1960	1,500
1961	3,300
1962	2,200
1963	2,400
1964	2,000
1965	80
1966	55
1967	28
1968	8
1969	160

a. Annual values do not include iodine as a byproduct from RaLa processing.

Table C-2. Weekly average number of gross beta/gamma air samples.

Year	Samples per week	SRDB Ref ID
1955	222	22545
1956	186	13248
1957	496	22546
1958	429	21780
1959	327	22547
1960	695	12083
1961	681	12084
1962	573	12093
1963	452	12092
1964	409	12090

1960), with trigger levels remaining at 0.1 MPC for general entry without respiratory protection, and 100 MPC as a ceiling value for entry with respiratory protection (ORNL 1961).

C.4 THYROID MONITORING

Thyroid monitoring before the implementation of WBCs in 1962 was performed using a Geiger-Müller (GM) detector, typically pressed against the left side of the neck, then on the right side of the neck. (There also are reports showing only one result, without indicating if it was the average of left and

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

right measurements or measured with the detector at the middle of neck.) A dedicated counting system was available as of April 1954 (ORNL 1954b), but no additional detail on counter configuration or procedures is available.

A total of 230 measurements are available; these measurements were performed on 147 individuals and span the period from 1945 through 1957 (see Table C-3). All of the available data were gathered from incident reports and/or internal memoranda summarizing each monitoring event. The ORAU Team reviewed periodic Applied HP group reports to determine if the frequency of thyroid counting was included. These reports included statistics on various radiological services and were semiannual from 1955 to 1956 and annual thereafter. The average weekly number of thyroid counts is only reported in the 1957 and 1958 reports (ORNL 1957; Hart 1960). No data are noted from before 1957 or after 1958. The number of thyroid measurements was reported as 100 in 1957 (weekly average of two) and 50 in 1958. Table C-3 shows that these numbers do not correspond with the actually available data for these years, which show 18 in 1957 and none in 1958. It appears that additional data might have existed, but they are not available.

Table C-3. Available thyroid counting data, 1945 to 1957.

Date	Counts	Individuals	SRDB Ref ID	Summary
09/21/1945[a]	9	9	103999	Nine individual "special probing" thyroid and chest counts taken. These workers were all located in 706-D (3026-D: RaLa chemical separation) and worked 9/20/45 on night shift.
03/5/1946	1	1	22957	A precipitron run at 7:45 p.m. on 3/5/46 indicated increased airborne activity in 706-D. The source of activity was determined to be failure of a steam jet to automatically shut off at the W5 tank in the tank farm outside Building 706-D. The complicating factor was the metal being dissolved was very fresh, giving rise to release of short-lived material. Guards and other personnel around the tank farm area at the time of high airborne activity were checked for iodine accumulation in thyroid (only one result was listed in the report; other readings are unavailable).
07/2/1946	1	1	22957	A uranium slug that had cooled for 72 hours was loaded into the dissolver in Cell #1. Dissolving started at 12:00 p.m., 7/1/46. A single precipitron high count was observed about two hours after the dissolving started. No alpha contamination was observed. During decontamination, high hand and shoe counts on workers were observed.
08/16/1946 to 08/19/1946	28	15	116562	A report titled *706-D H.P. Report Period Ending 8/17/46* describes an incident involving high air activity on the third level when wind direction was from north. Twenty-three air samples (taken from 8/13/46 through 8/18/46) exceeding 10% of tolerance were recorded. It was concluded that the activity was coming from 706-D off-gas and the vent-duct stack.

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Table C-3. Available thyroid counting data, 1945 to 1957 (continued).

Date	Counts	Individuals	SRDB Ref ID	Summary
8/29/1947	1	1	22957	One thyroid count was taken on August 29, 1947, after a violent oxalic acid chemical reaction in the iodine setup at Building 706-D [SRDB 22959, p. 114; 118330, p. 3]. A 30-minute precipitron run at the work site resulted in measured air activity of 7.72E-11 µCi/cm^3 beta/gamma. The two continuous air monitors (CAMs) in the area showed no increase in activity.
12/09/1947 to 12/10/1947[a]	54	54	22959	A report titled *706-D H.P. Report for Week Ending 12-6-47* describes decontamination work in Cell A that continued from the prior week. Contamination surveys of Building 105 took place during this time. The personnel who took part in work were subjected to thyroid counting, chest counts, and nasal swipes on December 9–10 and worked 9/20/1945.
09/27/1948 to 10/22/1948[a]	31	6	110152	Six workers were selected for repeat counts in September and October 1948. Work locations and reasons for the counts were not given. Each worker was scheduled for six separate counts for a total of 36 counts, but some workers did not report for later repeat counts, resulting in 31 thyroid counts.
04/18/1949 to 04/22/1949[a]	22	7	119713	Six workers at Building 706-D were repeatedly thyroid-counted from April 15 through 22, 1949. These workers were involved in Product Run #88. The thyroid counts taken from April 15 to 17 are not included in the co-worker study because the product run was not fully underway until April 18.
11/22/1949	4	4	104084	Four thyroid counts were taken in November 1949 after intermittent high air activity throughout the day on 11/22/1949 in Building 706-C. Air activity was suspected to have originated from the I-131 run in progress. A rise in air activity was noted on the CAMs immediately after the sparging operation in the cell. Several precipitron samples taken during the day did not reveal activity approaching tolerance level, and the activity collected in the precipitron foils decayed rapidly. The filter papers on the CAMs had to be replaced constantly to keep the instruments in scale. Several CAM filters were auto-radiographed and the result indicated that the activity was diffused rather than particulate in nature.
03/14/1950 to 03/15/1950	18	9	104119	Thyroid counts were taken on workers in the vicinity of the I-131 process cell during the period of high air activity in 706-C. The air activity became high enough that the building was evacuated. The source of the activity was traced to material escaping through opening in the top of the I-131 process well. The decay and absorption curves indicated that the isotopes were I-131, and possibly some Te-132. Thyroid counts were taken on maintenance workers and operators working in the vicinity of the cell.

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Table C-3. Available thyroid counting data, 1945 to 1957 (continued).

Date	Counts	Individuals	SRDB Ref ID	Summary
01/11/1951 to 01/13/1951	8	3	104244	Eight counts were taken on three individuals in January after a contamination incident. On January 11, the three employees were performing nitrate analysis on iodide products in a laboratory in Building 706-D. When they dissolved sodium iodide in sulfuric acid, free iodide and radioactive fumes scattered over the room and one of them became externally contaminated.
10/24/1951	1	1	104405	A thyroid count was performed on an employee who was working in the vicinity of a suspected high airborne fission product release in Building 3026.
1/28/1952	7	3	104471	Loss of off-gas vacuum at 5:00 p.m. on January 28, 1952 on the I-131 setup resulted in release of airborne activity. The building was evacuated upon CAM alarm.
4/29/1954	27	27	147059, 147108, 147114, 147210	Fumes boiled over upon the addition of a nitric acid solution to very hot (thermally) slugs within the dissolver tank. Highly radioactive fumes set off the monitron and CAMs.
10/25/1957	18	6	033238	Pressurization of feed adjustment tank resulted in the release of air activity.
Total	**230**	**147**	Not applicable	Not applicable

a. Indicates data assessed collectively in chronic intake assessment; all other data assessed individually as acute intakes.

Medical records for individuals likely to have been exposed to radioiodine (based on incident reports and work history) were reviewed to determine if records of thyroid counting were included in the medical charts. While the reviewed charts did include records of thyroid counting associated with some radiological incidents, there were no records of routine thyroid counts.

Calibration data for thyroid measurements were sometimes included with the documentation of the measurements themselves and were expressed as the number of cpm being equivalent to "tolerance." The tolerance value is equivalent to the organ MPC based on the exposure limits at the time. The thyroid tolerance value was 2.0 µCi before July 1947 (Morgan 1947) but was changed to 0.2 µCi by May 1948 (Morgan 1948). This change is evident on inspection of thyroid tolerance values expressed in cpm, which vary by a factor of 10 when comparing pre-1948 values with post-1948 values. Table C-4 presents a summary of the available data on factors that were used to convert thyroid measurements to thyroid burden.

Table C-4. Tolerance equivalents for various GM detectors (cpm).[a]

Date	Glass	Brass	Bi-GM (Bismuth-C coated)	SRDB Ref ID
08/16/46	Not applicable	750	Not applicable	22957, p. 264
08/26/46	296	194[b]	Not applicable	22957
09/17/46	445[c]	834	Not applicable	22946
04/18/49	Not applicable	75	Not applicable	109284
05/01/51	Not applicable	Not applicable	400	109500, p. 31

a. The tolerance value was defined as the instrument response in cpm equivalent to the maximum allowable thyroid burden. This value was initially 2 µCi and was changed to 0.2 µCi in May 1948.
b. Glass-walled tube with brass covering.
c. Protective wire covering closer to the tube than used on 08/26/1946.

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

C.5 EVALUATION OF THYROID MONITORING DATA

The ORAU Team reviewed the available thyroid monitoring data for the period from 1945 to 1957 (see Table C-3) to determine the nature of the exposure (chronic versus acute). Once this was done, a single dataset representing chronic iodine exposure conditions, and a series of datasets representing individual acute (episodic/incident) exposure conditions, were compiled. The thyroid detector calibration information (Table C-4) was used to develop a mechanism to convert each thyroid measurement to an individual iodine thyroid burden in microcuries (Table C-5).

Table C-5. Calibration factors used to convert thyroid counting data.

Period	Value	Basis
1945–1946	750 cpm = 2.0 µCi	Documentation published in 1947 indicated the 2.0 µCi maximum thyroid burden value [SRDB 13233].
1947–1952	75 cpm = 0.2 µCi	Change of thyroid burden value from 2.0 µCi to 0.2µCi between 1947 and 1948 [SRDB 13233; 101475] and measurement data sheets [SRDB 109284].
1954–1957	400 cpm = 0.2 µCi	SRDB 103344

Data in Table C-3 that were indicative of episodic releases (incidents) were converted to thyroid burden in microcuries and evaluated as individual acute intakes using the actual measurement and exposure date/time parameters.

Data in Table C-3 that were indicative of routine measurements (as indicated by an 'a' adjacent to the date range) were converted to thyroid burden in microcuries and assessed as a single chronic intake using standard one person–one sample methodology.

A lognormal distribution with geometric mean of 0.04167 µCi and geometric standard deviation of 6.036 was fit to the thyroid burden data. This resulted in a 95th-percentile thyroid burden of 0.8 µCi. The Integrated Modules for Bioassay Analysis (IMBA) program was used to calculate the intake quantity associated with the calculated 95th-percentile thyroid burden as well as the projected urinary excretion rate and whole-body burden. The equilibrium intake (i.e., > 90-day exposure period for ^{131}I) associated with this burden is 5.4×10^5 pCi/d. Note that the equilibrium intake associated with the geometric mean burden (50th percentile) is 2.8×10^4 pCi/d.

C.6 WHOLE-BODY COUNTING

In 1961, the ORNL whole-body counter was brought into operation. Individuals were counted in either a chair or scanning-bed configuration.

Table C-6 below summarizes the maximum detected quantity of ^{131}I for each specified year. Currently, only summary data are available for the WBC results; however, these data would be expected to be reported in individual claimant files as well.

Table C-6. Summary of WBC data for ^{131}I.

Year	Highest measured activity in µCi (whole body)	Number with measurable activity	Number of measurements performed	SRDB Ref ID
1961	0.20	4	102	12084
1962	0.28	17	395	12093
1963	0.15	32	1,054	12092
1964	0.022	11	1,483	12090

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

C.7 IODINE URINARY SAMPLING

Urine bioassays for iodine appear to have been begun as early as 1958, with only a small number of samples analyzed before 1962. Tables C-7 and C-8 present the number and relative magnitude of the available data. No urine bioassay data are available for 1977 to 1986.

Table C-7. Summary of available iodine urine samples.

Year	Number of samples
1958	2
1961	1
1962	5
1963	3
1964	4
1965	18
1966	11
1967	11
1968	1
1969	15
1970	13
1971	5
1972	1
1973	41
1974	2
1976	2
1987	5
1988	28
Total	**168**

Table C-8. Iodine urine bioassay samples by sample type.

Sample type	Count	Min (pCi/24 hr)	Max (pCi/24 hr)
Incident/follow-up/resample	40	0	2.2E+07
Unknown	6	0	9.5E+02
Work area/routine	54	0	4.5E+03
Results <5% exposure index	18	Not applicable	Not applicable
Total	118	Not applicable	Not applicable
Results unavailable	50[a]	Not applicable	Not applicable

a. Results listed in totals, but actual result not available.

C.8 COMPARISON OF PROPOSED CHRONIC IODINE INTAKE WITH LATER DATA

The ORAU Team evaluated iodine intake events between 1962 and 1969 to compare them to the potential intake quantities that were derived from data for 1945 to 1957 in Section C.5.

Section C.12 provides a summary of bioassay data (urine, thyroid, and WBCs) and the results of an intake assessment associated with acute iodine intakes between 1962 and 1969. One very high exposure event occurred on June 21, 1967, during which two individuals were administered potassium iodide (KI). Intakes for this event were 9.7×10^6 pCi and 1.8×10^7 pCi for the two workers. Excluding this one event, intake quantities between 1962 and 1969 ranged from 6.9×10^2 pCi to 6.9×10^5 pCi. This is a few orders of magnitude lower than intakes computed for the period from 1944 to 1957 (8.5×10^3 pCi to 2.5×10^7 pCi).

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

A graphical comparison of the acute intakes that were calculated for the events during both 1946 to 1957 and 1962 to 1969, along with the chronic intake calculated using the routine monitoring data between 1945 and 1954, are shown in Figure C-1. This figure clearly shows the difference in magnitude of acute intake quantities when comparing events before 1955 to those after 1955. The intake quantity based on the 95th percentile of the routine monitoring data (5.4×10^5 pCi/d) is superimposed on this chart (solid horizontal line). This chronic intake bounds acute intakes during the post-1955 period. This conclusion is based on the observation that events equivalent to the highest acute intake after 1955 (1.8×10^7 pCi) would have to occur on a monthly basis to yield an intake higher than that of the chronic scenario (5.4×10^5 pCi/d × 365 d = 2.0×10^8 pCi).

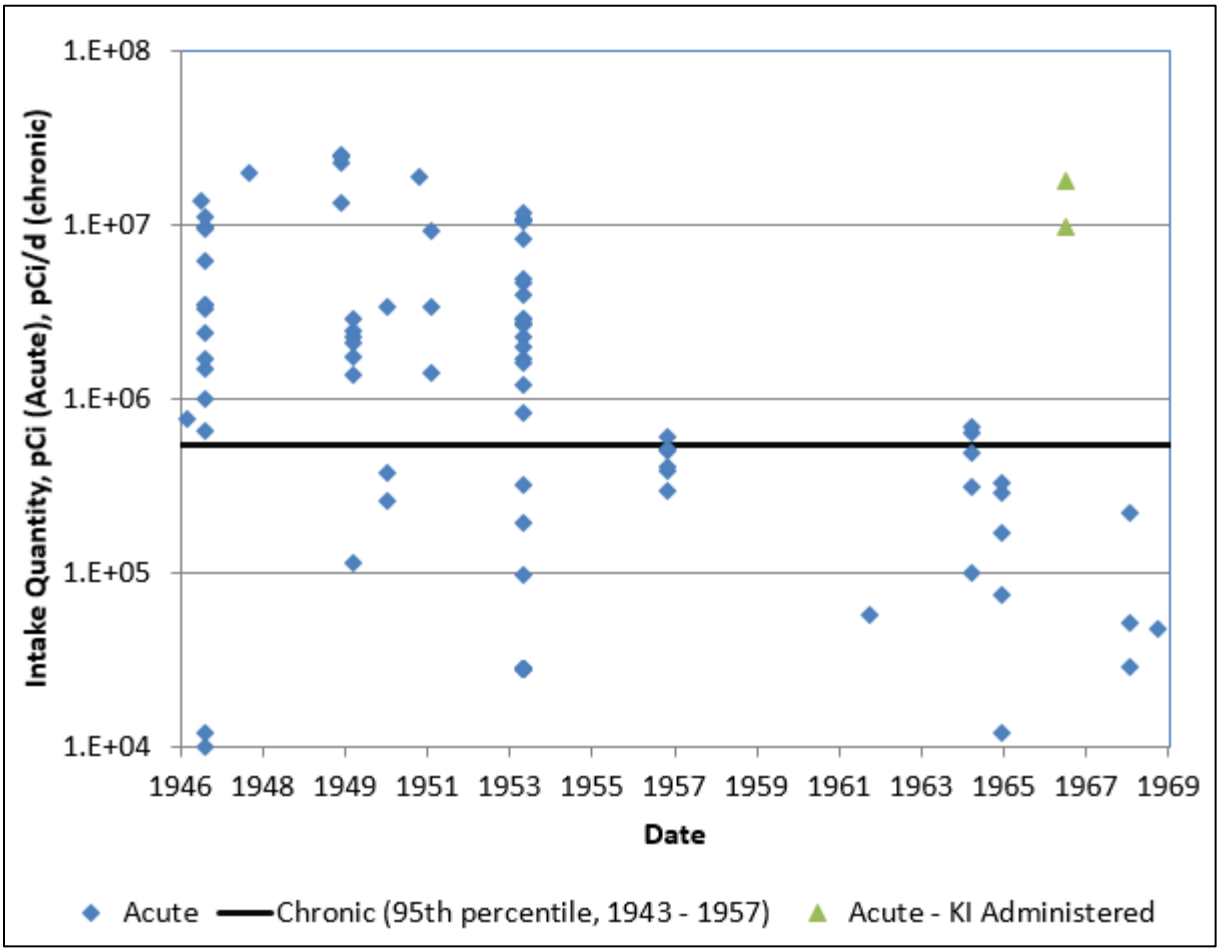

Figure C-1. Comparison of acute and chronic intake assessments.

C.9 PROPOSAL FOR UNMONITORED WORKERS

As indicated earlier, the ORAU Team has proposed that the chronic intake that has been developed using the chronic intakes that were derived from the 1947 to 1949 monitoring data could be used to assign iodine intakes to individuals for whom no monitoring data are available during the period between the end of the current SEC period and the onset of routine WBCs (i.e., from 1955 to 1961). During this period, a chronic intake of 5.4×10^5 pCi/d would be assigned. Such an intake would equate to a urinary excretion of 1.7×10^5 pCi/d, result in a whole-body accumulation of 1.2 µCi, and be equivalent to exposure to an air concentration of 1.8×10^{-8} µCi/cm^3. Comparing these values to

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

available data yields the following conclusions, which support application of this intake for unmonitored individuals:

1. The projected urinary excretion (1.7×10^5 pCi/d) is more than an order of magnitude greater than the highest measured urinary excretion for routine sampling of 4.5×10^3 pCi/d (see Table C-8).

2. The projected whole-body accumulation (1.2 µCi) is a factor of 4 larger than the highest measured whole-body accumulation of 0.28 µCi (see Table C-6).

3. The projected air concentration (1.8 µCi/cm^3) is nearly a factor of 2 greater than the maximum operating level used to control facility air concentrations.

The quantity of iodine in process from 1955 to 1961 (1,000 to 3,600 Ci/yr) is bounded by the amount in process from 1947 to 1949 (8,800 to 42,000 Ci/yr). In summation, it is postulated that an individual with no thyroid monitoring from 1955 to 1962 would not have been exposed to a higher level than that determined by a chronic intake using the 95th percentile of routine monitoring data for 1947 to 1949. The workplace monitoring data that were in place from 1944 forward were able to detect intakes of this magnitude and, in such cases, personnel monitoring for iodine (thyroid-counting) was performed.

C.10 ACUTE INTAKE ANALYSIS SUMMARY, 1946 TO 1957

Start Date(s) of Incident: 03/05/1946
Description/Reference: A precipitron run at 7:45 p.m. on 3/5/1946 indicated increased airborne activity in 706-D. The source of activity was determined to be failure of steam jet to automatically shut off at the W5 tank in the tank farm outside of Building 706-D. A complicating factor was that the metal being dissolved was very fresh, giving rise to a release of short-lived material. Guards and other personnel around the tank farm area at the time of high airborne activity were checked for iodine accumulation in their thyroids. [SRDB Ref ID: 22957]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 1	03/05/1946	Unknown	0.17	6.8E+05
Worker 1	03/08/1946	Unknown	3.0	8.0E+04

Intake assessment table

Name	Intake (pCi)
Worker 1	7.6E+05

Start Date(s) of Incident: 07/02/1946
Description/Reference: A uranium slug that had cooled for 72 hours was loaded into the dissolver in Cell #1. Dissolving started at 12:00 p.m., 7/1/1946. A single precipitron high count was observed about 2 hours after the dissolving started. No alpha contamination was observed. During decontamination, high hand and shoe counts on workers were observed. [SRDB Ref ID: 22957]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 2	07/02/1946	Unknown	0.17	4.9E+05

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Intake assessment table

Name	Intake (pCi)
Worker 2	1.4E+07

Start Date(s) of Incident: 08/16/1946

Description/Reference: A report titled *706-D H.P. Report Period Ending 8/17/46* describes an incident involving high air activity on the third level when wind direction was from north. Twenty-three air samples (taken from 8/13/1946 through 8/18/1946) exceeding 10% of tolerance were recorded. It was concluded that the activity was coming from 706-D off-gas and the vent-duct stack. [SRDB Ref ID: 116562]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 3	08/19/1946	7:36:00	5.40	1.0E+03
Worker 4	08/16/1946	22:55:00	3.04	8.1E+05
Worker 4	08/17/1946	22:35:00	4.03	2.3E+05
Worker 4	08/18/1946	23:45:00	5.07	1.0E+05
Worker 5	08/16/1946	22:46:00	3.03	6.2E+05
Worker 5	08/17/1946	22:26:00	4.02	2.7E+05
Worker 5	08/18/1946	23:33:00	5.07	3.8E+05
Worker 6	08/16/1946	22:49:00	3.03	1.0E+03
Worker 6	08/17/1946	22:29:00	4.02	1.0E+03
Worker 7	08/17/1946	22:38:00	4.03	1.8E+06
Worker 7	08/18/1946	23:36:00	5.07	7.3E+05
Worker 8	08/18/1946	15:21:00	4.72	5.7E+05
Worker 9	08/16/1946	22:40:00	3.03	3.1E+06
Worker 9	08/17/1946	22:20:00	4.01	2.2E+06
Worker 9	08/18/1946	16:35:00	4.78	8.5E+05
Worker 9	08/18/1946	23:39:00	5.07	6.3E+05
Worker 10	08/16/1946	22:52:00	3.04	1.8E+06
Worker 10	08/17/1946	22:32:00	4.02	5.3E+04
Worker 10	08/18/1946	23:42:00	5.07	1.9E+05
Worker 11	08/19/1946	7:33:00	5.40	1.5E+05
Worker 12	08/18/1946	15:18:00	4.72	3.1E+05
Worker 13	08/18/1946	16:30:00	4.77	3.2E+05
Worker 14	08/16/1946	22:43:00	3.03	7.1E+05
Worker 14	08/17/1946	22:23:00	4.02	1.0E+03
Worker 14	08/18/1946	23:30:00	5.06	2.6E+05
Worker 15	08/18/1946	15:15:00	4.72	2.2E+05
Worker 16	08/18/1946	17:00:00	4.79	9.8E+05
Worker 17	08/19/1946	7:30:00	5.40	9.1E+04
Worker 3	08/19/1946	7:36:00	5.40	1.0E+03

Intake assessment table

Name	Intake (pCi)
Worker 3	1.2E+04
Worker 4	1.5E+06
Worker 5	3.5E+06
Worker 6	9.4E+03
Worker 7	9.8E+06
Worker 8	6.2E+06

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Intake (pCi)
Worker 9	9.4E+06
Worker 10	6.5E+05
Worker 11	1.7E+06
Worker 12	3.3E+06
Worker 13	3.5E+06
Worker 14	1.0E+04
Worker 15	2.4E+06
Worker 16	1.1E+07
Worker 17	1.0E+06

Start Date(s) of Incident: 08/29/1947
Description/Reference: One thyroid count was taken on August 29, 1947 after a violent oxalic acid chemical reaction in the iodine setup at Building 706-D (SRDB 22959, p. 114; 118330, p. 3). A 30-minute precipitron run at the work site resulted in measured air activity of 7.72×10^{-11} µCi/cm^3 beta/gamma. The two CAMs in the area showed no increase in activity. [SRDB Ref ID: 22959, 118330]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 18	08/29/1947	Unknown	0.17	7.2E+05

Intake assessment table

Name	Intake (pCi)
Worker 18	2.0E+07

Start Date(s) of Incident: 11/22/1949
Description/Reference: Four thyroid counts were taken in November 1949 after intermittent high air activity throughout the day on 11/22/1949 in Building 706-C. Air activity was suspected to have originated from the ^{131}I run in progress. A rise in air activity was noted on the CAMs immediately after the sparging operation in the cell. Several precipitron samples taken during the day did not reveal activity approaching tolerance level, and the activity collected in the precipitron foils decayed rapidly. The filter papers on the CAMs had to be replaced constantly to keep the instruments in scale. Several CAM filters were auto-radiographed and the result indicated that the activity was diffused rather than particulate in nature. [SRDB Ref ID: 104084]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 19	11/22/1949	Unknown	0.17	8.1E+05
Worker 20	11/22/1949	Unknown	0.17	4.7E+05
Worker 21	11/22/1949	Unknown	0.17	9.1E+05
Worker 22	11/22/1949	Unknown	0.17	8.9E+05

Intake assessment table

Name	Intake (pCi)
Worker 19	2.3E+07
Worker 20	1.3E+07
Worker 21	2.5E+07
Worker 22	2.5E+07

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Start Date(s) of Incident: 03/14/1950
Description/Reference: Thyroid counts were taken on workers in the vicinity of the ^{131}I process cell during the period of high air activity in 706-C. The air activity became high enough that the building was evacuated. The source of the activity was traced to material escaping through opening in the top of the ^{131}I process well. The decay and absorption curves indicated that the isotopes were ^{131}I, and possibly some ^{132}Te. Thyroid counts were taken on maintenance workers and operators working in the vicinity of the cell. [SRDB Ref ID: 104119]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 23	03/14/1950	15:30:00	0.21	4.0E+05
Worker 23	03/15/1950	8:30:00	0.92	2.5E+05
Worker 24	03/14/1950	15:30:00	0.21	2.1E+05
Worker 24	03/15/1950	8:30:00	0.92	1.7E+05
Worker 25	03/14/1950	15:30:00	0.21	6.0E+05
Worker 25	03/15/1950	8:30:00	0.92	1.5E+05
Worker 26	03/14/1950	15:30:00	0.21	3.9E+05
Worker 26	03/15/1950	8:30:00	0.92	1.3E+04
Worker 27	03/14/1950	15:30:00	0.21	7.4E+05
Worker 27	03/15/1950	8:30:00	0.92	1.0E+03
Worker 28	03/14/1950	15:30:00	0.21	2.6E+05
Worker 28	03/15/1950	8:30:00	0.92	2.2E+05
Worker 29	03/14/1950	15:30:00	0.21	4.2E+05
Worker 29	03/15/1950	8:30:00	0.92	1.0E+03
Worker 30	03/14/1950	15:30:00	0.21	4.2E+05
Worker 30	03/15/1950	8:30:00	0.92	2.9E+05
Worker 31	03/14/1950	15:30:00	0.21	5.7E+05

Intake assessment table

Name	Intake (pCi)
Worker 23	2.4E+06
Worker 24	1.7E+06
Worker 25	1.4E+06
Worker 26	1.2E+05
Worker 27	8.5E+03
Worker 28	2.3E+06
Worker 29	8.5E+03
Worker 30	2.9E+06
Worker 31	2.1E+06

Start Date(s) of Incident: 01/11/1951
Description/Reference: Eight counts were taken on three individuals in January after a contamination incident. On January 11, the three employees were performing nitrate analysis on iodide products in a laboratory in Building 706-D. When they dissolved sodium iodide in sulfuric acid, free iodide and radioactive fumes scattered over the room and one of them became externally contaminated. [SRDB Ref ID: 104244]

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 32	01/11/1951	Unknown	0.17	2.3E+05
Worker 32	01/12/1951	8:00:00	1.00	4.3E+04
Worker 33	01/11/1951	Unknown	0.17	5.3E+05
Worker 33	01/12/1951	9:00:00	1.00	3.5E+05
Worker 34	01/11/1951	Unknown	0.17	6.7E+05
Worker 34	01/11/1951	Unknown	0.17	7.7E+05
Worker 34	01/12/1951	12:00:00	1.00	5.5E+05
Worker 34	01/12/1951	16:00:00	1.00	3.5E+05
Worker 34	01/13/1951	Unknown	2.00	2.7E+04

Intake assessment table

Name	Intake (pCi)
Worker 32	3.8E+05
Worker 33	3.3E+06
Worker 34	2.6E+05

Start Date(s) of Incident: 10/24/1951
Description/Reference: A thyroid count was performed on an employee who was working in the vicinity of a suspected high airborne fission product release in Building 3026. [SRDB Ref ID: 104405]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 35	10/24/1951	Unknown	0.17	2.1E+05

Intake assessment table

Name	Intake (pCi)
Worker 35	1.9E+07

Start Date(s) of Incident: 01/28/1952
Description/Reference: Loss of off-gas vacuum at 5:00 p.m. on January 28, 1952 on the ^{131}I setup resulted in release of airborne activity. The building was evacuated upon CAM alarm. [SRDB Ref ID: 104471]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 36	01/28/1952	21:30:00	0.19	3.6E+06
Worker 36	01/29/1952	21:30:00	1.19	2.0E+06
Worker 36	01/30/1952	16:00:00	1.96	8.7E+05
Worker 37	01/28/1952	21:30:00	0.19	9.0E+05
Worker 37	01/29/1952	21:30:00	1.19	1.6E+05
Worker 38	01/28/1952	21:30:00	0.19	8.3E+05
Worker 38	01/29/1952	21:30:00	1.19	3.7E+05

Intake assessment table

Name	Intake (pCi)
Worker 36	9.3E+06
Worker 37	1.4E+06

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Intake (pCi)
Worker 38	3.4E+06

Start Date(s) of Incident: 04/29/1954
Description/Reference: Fumes boiled over upon the addition of a nitric acid solution to very hot (thermally) slugs within the dissolver tank. Highly radioactive fumes set off the monitron and CAMs. [SRDB Ref ID: 147059, 147108, 147114, 147210]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 39	04/29/1954	Unknown	0.17	3.8E+05
Worker 40	04/29/1954	Unknown	0.17	1.4E+05
Worker 41	04/29/1954	Unknown	0.17	1.0E+03
Worker 42	04/29/1954	Unknown	0.17	1.0E+03
Worker 43	04/29/1954	Unknown	0.17	3.5E+03
Worker 44	04/29/1954	Unknown	0.17	9.8E+04
Worker 45	04/29/1954	Unknown	0.17	1.0E+03
Worker 46	04/29/1954	Unknown	0.17	1.0E+03
Worker 47	04/29/1954	Unknown	0.17	1.7E+05
Worker 48	04/29/1954	Unknown	0.17	8.1E+04
Worker 49	04/29/1954	Unknown	0.17	1.2E+04
Worker 50	04/29/1954	Unknown	0.17	1.0E+03
Worker 51	04/29/1954	Unknown	0.17	3.0E+05
Worker 52	04/29/1954	Unknown	0.17	3.8E+05
Worker 53	04/29/1954	Unknown	0.17	7.2E+04
Worker 54	04/29/1954	Unknown	0.17	1.0E+05
Worker 55	04/29/1954	Unknown	0.17	3.7E+05
Worker 56	04/29/1954	Unknown	0.17	4.2E+05
Worker 57	04/29/1954	Unknown	0.17	4.3E+04
Worker 58	04/29/1954	Unknown	0.17	3.0E+04
Worker 59	04/29/1954	Unknown	0.17	1.0E+03
Worker 60	04/29/1954	Unknown	0.17	7.0E+03
Worker 61	04/29/1954	Unknown	0.17	9.4E+04
Worker 62	04/29/1954	Unknown	0.17	1.0E+05
Worker 63	04/29/1954	Unknown	0.17	6.1E+04
Worker 64	04/29/1954	Unknown	0.17	1.7E+05
Worker 65	04/29/1954	Unknown	0.17	5.7E+04

Intake assessment table

Name	Intake (pCi)
Worker 39	1.1E+07
Worker 40	4.0E+06
Worker 41	2.8E+04
Worker 42	2.8E+04
Worker 43	9.8E+04
Worker 44	2.7E+06
Worker 45	2.8E+04
Worker 46	2.8E+04
Worker 47	4.6E+06
Worker 48	2.3E+06
Worker 49	3.2E+05

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Intake (pCi)
Worker 50	2.8E+04
Worker 51	8.3E+06
Worker 52	1.1E+07
Worker 53	2.0E+06
Worker 54	2.9E+06
Worker 55	1.0E+07
Worker 56	1.2E+07
Worker 57	1.2E+06
Worker 58	8.2E+05
Worker 59	2.8E+04
Worker 60	2.0E+05
Worker 61	2.6E+06
Worker 62	2.9E+06
Worker 63	1.7E+06
Worker 64	4.9E+06
Worker 65	1.6E+06

Start Date(s) of Incident: 10/25/1957
Description/Reference: Pressurization of feed adjustment tank resulted in the release of air activity. [SRDB Ref ID: 33238]

Thyroid count data table

Name	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi)
Worker 66	10/25/1957	Unknown	0.17	1.9E+02
Worker 67	10/25/1957	Unknown	0.17	4.1E+06
Worker 67	10/28/1957	Unknown	3.00	5.4E+05
Worker 67	11/04/1957	Unknown	10.00	2.0E+04
Worker 68	10/28/1957	Unknown	3.00	6.0E+05
Worker 68	11/04/1957	Unknown	10.00	2.7E+04
Worker 69	10/25/1957	Unknown	0.17	8.4E+06
Worker 69	10/28/1957	Unknown	3.00	3.8E+05
Worker 69	11/04/1957	Unknown	10.00	1.6E+04
Worker 70	10/25/1957	Unknown	0.17	6.1E+05
Worker 70	10/28/1957	Unknown	3.00	5.9E+04
Worker 70	11/04/1957	Unknown	10.00	2.0E+04
Worker 71	10/25/1957	Unknown	0.17	3.3E+06
Worker 71	10/28/1957	Unknown	3.00	1.6E+05
Worker 71	11/04/1957	Unknown	10.00	2.9E+04
Worker 72	10/25/1957	Unknown	0.17	7.0E+06
Worker 72	10/28/1957	Unknown	3.00	4.7E+05
Worker 72	11/04/1957	Unknown	10.00	2.7E+04

Intake assessment table

Name	Intake (pCi)
Worker 66	5.2E+03
Worker 67	3.8E+05
Worker 68	5.1E+05
Worker 69	3.0E+05
Worker 70	4.1E+05

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Intake (pCi)
Worker 71	6.1E+05
Worker 72	5.2E+05

C.11 CHRONIC INTAKE ASSESSMENT SUMMARY, 1946 TO 1957

Start Date(s) of Incident: 09/21/1945
Description/Reference: Nine individual "special probing" thyroid and chest counts taken. These workers were all located in 706-D (3026-D: RaLa chemical separation) and worked 9/20/45 on night shift. [SRDB Ref ID: 103999]

Bioassay data table

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
Worker 39	09/21/1945	120	122	0.33
Worker 73	09/21/1945	468	210	1.26
Worker 74	09/21/1945	272	136	0.73
Worker 75	09/21/1945	112	132	0.36
Worker 76	09/21/1945	20	176	0.48
Worker 77	09/21/1945	618	618	1.67
Worker 78	09/21/1945	No data	246	0.66
Worker 79	09/21/1945	0	0	0.0027[a]
Worker 80	09/21/1945	84	136	0.37

a. De minimus/censored data point.

Start Date(s) of Incident: 12/09/1947 to 12/10/1947
Description/Reference: A report titled *706-D H.P. Report for Week Ending 12-6-47* describes decontamination work in Cell A that continued from the prior week. Contamination surveys of Building 105 took place during this time. The personnel who took part in work were subjected to thyroid counting, chest counts, and nasal swipes on December 9 and 10 and worked 9/20/1945. [SRDB Ref ID: 22959]

Bioassay data table

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
309	12/10/1947	0	0	0.0027[a]
1071	12/10/1947	15	1	0.04
1214	12/09/1947	11	12	0.03
1521	12/09/1947	0	11	0.03
1858	12/09/1947	63	90	0.24
1877	12/10/1947	0	3	0.01
2004	12/09/1947	14	5	0.04
2030	12/09/1947	49	42	0.13
2070	12/10/1947	0	3	0.01
2088	12/10/1947	0	0	0.0027[a]
2108	12/10/1947	11	16	0.04
2119	12/09/1947	7	22	0.06
2147	12/10/1947	5	25	0.07
2238	12/09/1947	0	0	0.0027[a]
2286	12/09/1947	27	45	0.12
2411	12/10/1947	15	38	0.10
2417	12/10/1947	3	10	0.03

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
2420	12/09/1947	0	10	0.03
2436	12/09/1947	15	21	0.06
2520	12/10/1947	12	0	0.03
2745	12/09/1947	12	0	0.03
3772	12/09/1947	66	128	0.35
3783	12/10/1947	19	26	0.07
3941	12/10/1947	0	0	0.0027[a]
4088	12/10/1947	0	0	0.0027[a]
4317	12/09/1947	0	7	0.02
4322	12/09/1947	8	2	0.02
4418	12/10/1947	1	1	0.003
4471	12/10/1947	0	5	0.01
4546	12/10/1947	4	3	0.01
4550	12/10/1947	10	0	0.03
4575	12/10/1947	6	4	0.02
4729	12/10/1947	20	16	0.05
4731	12/10/1947	0	0	0.0027[a]
4922	12/10/1947	13	0	0.04
5886	12/10/1947	30	74	0.20
6199	12/09/1947	0	0	0.0027[a]
6218	12/10/1947	0	0	0.0027[a]
6318	12/10/1947	0	4	0.01
6410	12/09/1947	0	0	0.0027[a]
6441	12/09/1947	11	0	0.03
6454	12/09/1947	4	5	0.01
6456	12/09/1947	0	0	0.0027[a]
6522	12/10/1947	0	0	0.0027[a]
6635	12/09/1947	490	300	1.32
6720	12/10/1947	9	5	0.02
6846	12/09/1947	2	15	0.04
6866	12/09/1947	0	3	0.01
6974	12/09/1947	97	61	0.26
8060	12/09/1947	102	35	0.28
8080	12/09/1947	14	8	0.04
8103	12/09/1947	3	9	0.02
8111	12/10/1947	24	30	0.08
8254	12/10/1947	8	32	0.09

a. De minimus/censored data point.

Start Date(s) of Incident: 09/27/1948 to 10/22/1948

Description/Reference: Six workers were selected for repeat counts in September and October 1948. Work locations and reasons for the counts were not given. Each worker was scheduled for six separate counts for a total of 36 counts, but some workers did not report for later repeat counts, resulting in 31 thyroid counts. [SRDB Ref ID: 110152]

Bioassay data table

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
Worker 81	09/28/1948	25	BKG	0.068
Worker 81	09/30/1948	BKG	BKG	0.068

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
Worker 81	10/04/1948	5	BKG	0.068
Worker 81	10/08/1948	22	12	0.068
Worker 81	10/18/1948	3	BKG	0.068
Worker 82	09/27/1948	BKG	BKG	0.089
Worker 82	10/01/1948	10	18	0.089
Worker 82	10/04/1948	6	12	0.089
Worker 82	10/06/1948	15	15	0.089
Worker 82	10/18/1948	BKG	33	0.089
Worker 82	10/21/1948	BKG	16	0.089
Worker 83	09/27/1948	15	9	0.078
Worker 83	09/30/1948	13	20	0.078
Worker 83	10/04/1948	11	29	0.078
Worker 83	10/18/1948	13	9	0.078
Worker 83	10/22/1948	10	23	0.078
Worker 84	09/29/1948	BKG	20	0.105
Worker 84	09/30/1948	18	BKG	0.105
Worker 84	10/05/1948	20	21	0.105
Worker 84	10/08/1948	23	39	0.105
Worker 84	10/18/1948	7	BKG	0.105
Worker 85	09/27/1948	BKG	BKG	0.059
Worker 85	09/30/1948	5	2	0.059
Worker 85	10/04/1948	15	BKG	0.059
Worker 85	10/08/1948	18	22	0.059
Worker 85	10/18/1948	BKG	14	0.059
Worker 86	09/27/1948	BKG	BKG	0.100
Worker 86	09/30/1948	25	11	0.100
Worker 86	10/04/1948	37	16	0.100
Worker 86	10/08/1948	12	6	0.100
Worker 86	10/18/1948	11	17	0.100

Start Date(s) of Incident: 04/18/1949 to 04/22/1949

Description/Reference: Six workers at Building 706-D were repeatedly thyroid-counted from April 15 through 22, 1949. These workers were involved in Product Run #88. The thyroid counts taken from April 15 to 17 are not included in the co-worker study because the product run was not fully underway until April 18. [SRDB Ref ID: 119713]

Bioassay data table

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
Worker 87	04/21/1949	0	9	0.024
Worker 88	04/18/1949	9	14	0.038
Worker 89	04/19/1949	16	81	0.219
Worker 89	04/20/1949	9	0	0.219
Worker 89	04/21/1949	0	0	0.219
Worker 90	04/18/1949	3	7	0.149
Worker 90	04/19/1949	55	5	0.149
Worker 90	04/20/1949	29	27	0.149
Worker 90	04/22/1949	48	17	0.149
Worker 38	04/18/1949	37	30	0.497
Worker 38	04/19/1949	184	142	0.497

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Measurement date	Right measurement (cpm)	Left measurement (cpm)	Derived thyroid burden (µCi)
Worker 38	04/20/1949	120	140	0.497
Worker 38	04/21/1949	14	8	0.497
Worker 38	04/22/1949	111	87	0.497
Worker 91	04/18/1949	23	10	0.251
Worker 91	04/19/1949	77	73	0.251
Worker 91	04/20/1949	36	28	0.251
Worker 91	04/21/1949	54	93	0.251
Worker 91	04/22/1949	0	16	0.251
Worker 92	04/18/1949	2	12	0.032
Worker 92	04/19/1949	0	0	0.032
Worker 92	04/22/1949	0	0	0.032

C.12 ACUTE INTAKE ASSESSMENT SUMMARY, 1962 TO 1969

Start Date(s) of Incident: 9/21/1962
Description/Reference: An event report for a 3/16/1965 exposure described this as a similar event involving Worker 93. [NOCTS ID: DOE_Response_ personal ID redacted _D203, p. 549]

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 93	Urine	09/21/1962	02:30 p.m.	0.16	1.9E+05
Worker 93	Urine	09/21/1962	08:00 p.m.	0.39	1.1E+05
Worker 93	Urine	09/22/1962	08:00 a.m.	0.89	1.6E+04
Worker 93	Urine	09/22/1962	08:00 p.m.	1.39	6.1E+03
Worker 93	Urine	09/23/1962	08:00 a.m.	1.89	2.6E+03
Worker 93	Urine	09/23/1962	08:00 p.m.	2.39	1.4E+03
Worker 93	Urine	09/24/1962	06:00 a.m.	2.80	8.9E+02
Worker 93	Urine	09/24/1962	06:00 p.m.	3.80	2.4E+02

a. Urine results are normalized to pCi/24 hr.

Intake assessment table

Name	Intake (pCi)
Worker 93	5.7E4

Start Date(s) of Incident: 12/11/1963
Description/Reference: Personnel contamination in Cell II. On 12/11/1963 at about 2:45 p.m., Worker 94 [NOCTS ID: redacted] and Worker 95 [NOCTS ID: redacted] were cleaning a spill. There was no indication of release from the continuous air monitor in the cell. Investigation was based on personnel contamination detected on exit. [NOCTS ID: DOE_Response_personal ID redacted_D203, p. 243]

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 94	WBC	12/12/1963	10:00 a.m.	0.8	2.0E+03
Worker 95	WBC	12/12/1963	10:00 a.m.	0.8	No data

a. WBC results were recorded as pCi.

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Intake assessment table

Name	Intake (pCi)
Worker 94	7.33E3

Start Date(s) of Incident: 03/16/1965
Description/Reference: CAM alarm during decontamination of shipping insert that was contaminated with ^{131}I. Worker 79 (iodine worker files), Worker 96 (iodine worker files), Worker 84 [NOCTS ID: redacted], Worker 98, and Worker 97 [NOCTS ID: redacted] in area during activity when CAM alarmed on high scale at 12:30 p.m. [NOCTS ID: DOE_Response_personal ID redacted_D203, p. 549]

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 96	Urine	03/16/1965	Unknown	0.12	3.5E+05
Worker 96	Urine	03/17/1965	10:00 a.m.	0.90	2.4E+05
Worker 96	Urine	03/28/1965	06:00 p.m.	12.23	1.7E+02
Worker 96	WBC	03/16/1965	03:31 p.m.	0.13	1.1E+06
Worker 96	WBC	03/19/1965	09:41 a.m.	2.88	5.4E+04
Worker 84	Urine	03/16/1965	Unknown	0.10	1.1E+05
Worker 84	Urine	03/17/1965	10:00 a.m.	0.90	8.6E+04
Worker 84	Urine	03/29/1965	10:00 a.m.	12.90	5.9E+01
Worker 84	WBC	03/16/1965	02:44 p.m.	0.09	5.8E+05
Worker 84	WBC	03/19/1965	10:40 a.m.	2.92	2.8E+04
Worker 79	Urine	03/16/1965	Unknown	0.08	2.9E+05
Worker 79	Urine	03/17/1965	11:00 a.m.	0.94	1.4E+05
Worker 79	Urine	03/27/1965	08:30 a.m.	10.83	5.0E+02
Worker 79	WBC	03/16/1965	02:20 p.m.	0.08	4.8E+05
Worker 79	WBC	03/19/1965	10:13 a.m.	2.90	5.0E+04
Worker 97	Urine	03/16/1965	Unknown	0.06	7.1E+04
Worker 97	Urine	03/17/1965	10:00 a.m.	0.90	2.2E+04
Worker 97	Urine	03/28/1965	06:30 p.m.	12.25	2.3E+02
Worker 97	WBC	03/16/1965	02:09 p.m.	0.11	1.3E+05
Worker 98	Urine	03/16/1965	Unknown	0.13	3.0E+05
Worker 98	Urine	03/17/1965	Unknown	0.9	1.3E+05
Worker 98	Urine	03/28/1965	Unknown	11.9	2.0E+02
Worker 98	WBC	03/16/1965	Unknown	0.06	9.1E+05

a. Urine results are normalized to pCi/24 hr; WBC results were recorded as pCi.

Intake assessment table

Name	Intake (pCi)
Worker 96	6.3E5
Worker 84	3.1E5
Worker 79	4.9E5
Worker 97	1.0E5
Worker 98	6.9E5

Start Date(s) of Incident: 12/17/1965
Description/Reference: A bottle containing 1 Ci of ^{131}I was dropped by Worker 100 [NOCTS ID: redacted] while performing measurements. Worker 99 (ORNL iodine worker file), Worker 103, Worker 102, and [worker name redacted] were working in the adjacent room. Initial thyroid scan for Worker

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

100 indicated 0.2 mR/hr. Whole-body scans indicated intakes of 170 nCi and 100 nCi for Worker 103 and Worker 99, respectively.

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 99	Urine	12/18/1965	12:45 p.m.	0.69	6.3E+04
Worker 99	Urine	12/23/1965	6:15 a.m.	1.71	9.5E+02
Worker 99	WBC	12/22/1965	9:05 a.m.	0.17	5.3E+04
Worker 100	Urine	12/19/1965	9:00 a.m.	0.78	2.8E+03
Worker 101	Urine	12/18/1965	9:00 a.m.	1.82	3.2E+03
Worker 102	Urine	12/20/1965	7:15 a.m.	7.73	9.5E+02
Worker 103	Urine	12/18/1965	4:00 p.m.	1.22	3.6E+04
Worker 103	Urine	12/23/1965	6:00 a.m.	5.80	7.2E+02
Worker 103	Fecal	12/18/1965	Unknown	Unknown	9.9E+01

a. Urine results are normalized to pCi/24 hr; WBC results were recorded as pCi.

Intake assessment table

Name	Intake (pCi)
Worker 99	2.9E+05
Worker 100	7.4E+04
Worker 101	1.2E+04
Worker 102	3.3E+05
Worker 103	1.7E+05

Start Date(s) of Incident: 06/21/1967

Description/Reference: While disassembling ^{131}I-contaminated equipment on 6/21/1967, two individuals became contaminated at 4:15 p.m. Individuals involved were Worker 104 [NOCTS ID: redacted] and Worker 105 [NOCTS ID: redacted]. Both individuals were administered KI at 7:00 p.m.

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 104	Urine	06/22/1967	8:45 a.m.	0.69	7.7E+06
Worker 104	Urine	06/23/1967	9:15 a.m.	1.71	1.2E+06
Worker 104	Urine	06/23/1967	4:00 p.m.	1.99	1.3E+05
Worker 104	Urine	07/12/1967	2:00 p.m.	20.91	3.2E+02
Worker 104	Urine	07/20/1967	1:00 p.m.	28.86	4.2E+02
Worker 104	WBC	06/21/1967	8:15 p.m.	0.17	6.9E+06
Worker 104	WBC	06/22/1967	10:54 a.m.	0.78	2.7E+06
Worker 104	WBC	06/23/1967	12:00 p.m.	1.82	1.6E+06
Worker 104	WBC	06/29/1967	9:46 a.m.	7.73	6.0E+05
Worker 104	WBC	07/07/1967	10:35 a.m.	15.76	1.4E+05
Worker 104	WBC	07/27/1967	1:03 p.m.	35.87	2.3E+04
Worker 104	Thy	06/21/1967	8:55 p.m.	0.19	4.3E+05
Worker 104	Thy	06/22/1967	11:25 a.m.	0.80	2.4E+05
Worker 104	Thy	06/23/1967	11:17 a.m.	1.79	2.2E+05
Worker 104	Thy	06/29/1967	9:36 a.m.	7.72	1.2E+05
Worker 104	Thy	07/07/1967	10:15 a.m.	15.75	4.6E+04
Worker 104	Thy	07/27/1967	1:30 p.m.	35.89	8.9E+03
Worker 105	Urine	06/22/1967	7:00 a.m.	0.61	2.2E+07
Worker 105	Urine	06/23/1967	7:00 a.m.	1.61	2.2E+06

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 105	Urine	06/23/1967	4:00 p.m.	1.99	1.4E+06
Worker 105	Urine	07/12/1967	1:30 p.m.	20.89	7.2E+02
Worker 105	Urine	07/20/1967	4:30 p.m.	29.01	5.9E+02
Worker 105	WBC	06/21/1967	8:23 p.m.	0.17	1.3E+07
Worker 105	WBC	06/22/1967	12:20 p.m.	0.84	5.8E+06
Worker 105	WBC	06/23/1967	10:20 a.m.	1.75	3.2E+06
Worker 105	WBC	06/29/1967	10:50 a.m.	7.77	1.1E+06
Worker 105	WBC	07/07/1967	11:32 a.m.	15.80	4.7E+05
Worker 105	WBC	07/27/1967	2:25 p.m.	35.92	Unknown
Worker 105	Thy	06/21/1967	8:15 p.m.	0.17	1.5E+06
Worker 105	Thy	06/22/1967	12:00 p.m.	0.82	9.0E+05
Worker 105	Thy	06/23/1967	10:59 a.m.	1.78	8.6E+05
Worker 105	Thy	06/29/1967	10:40 a.m.	7.77	5.0E+05
Worker 105	Thy	07/07/1967	11:52 a.m.	15.82	2.2E+05
Worker 105	Thy	07/27/1967	2:09 p.m.	35.91	Unknown

a. Urine results are normalized to pCi/24 hr; WBC and thyroid results are pCi.

Intake assessment table

Name	Intake (pCi)
Worker 104	9.7E6
Worker 105	1.8E7

Start Date(s) of Incident: 01/17/1969

Description/Reference: Airborne release while unloading a thermally heated sample carrier on 01/17/1969 at 9:45 a.m. Individuals present were Worker 106 (iodine worker files), Worker 107 (iodine worker files), Worker 108 [NOCTS ID: redacted], [name redacted], [name redacted], and [name redacted].

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 106	Urine	01/20/1969	6:30 a.m.	2.86	3.1E+03
Worker 106	Urine	01/31/1969	Unknown	Unknown	0
Worker 106	WBC	01/17/1969	12:49 p.m.	0.13	1.3E+05
Worker 106	WBC	01/20/1969	12:10 p.m.	3.10	3.6E+04
Worker 107	Urine	01/19/1969	6:00 p.m.	2.34	2.0E+03
Worker 107	Urine	01/30/1969	8:00 p.m.	13.43	4.3E+01
Worker 107	WBC	01/17/1969	2:41 p.m.	0.21	2.7E+04
Worker 108	Urine	01/20/1969	8:00 a.m.	2.93	9.0E+02
Worker 108	Urine	01/30/1969	4:00 p.m.	13.26	5.9E+01
Worker 108	WBC	01/17/1969	2:15 p.m.	0.19	1.8E+04

a. Urine results are normalized to pCi/24 hr; WBC results were recorded as pCi.

Intake assessment table

Name	Intake (pCi)
Worker 106	2.2E5
Worker 107	5.2E4
Worker 108	2.9E4

ATTACHMENT C
DOSE RECONSTRUCTION APPROACH FOR IODINE (continued)

Start Date(s) of Incident: 05/06/1969
Description/Reference: Airborne release occurred at 11:15 a.m. on 5/6/1969 while performing a filter performance test using ^{131}I. Individual involved was Worker 109 [NOCTS ID: redacted].

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 109	Urine	05/07/1969	6:00 a.m.	0.78	1.7E+02

a. Urine results are normalized to pCi/24 hr.

Intake assessment table

Name	Intake (pCi)
Worker 109	6.9E2

Start Date(s) of Incident: 09/26/1969
Description/Reference: Worker 110 [NOCTS ID: redacted] became contaminated while decontaminating manipulator tongs at 3:30 p.m. on 9/26/1969.

Bioassay data table

Name	Type	Measurement date	Measurement time	Time of measurement (after intake days)	Measurement result (pCi/24 hr)[a]
Worker 110	WBC	09/26/1969	05:37 p.m.	.09	3.6E+04
Worker 110	Lung	10/01/1969	08:55 a.m.	4.73	5.0E+3b

a. WBC results were recorded as pCi.
b. Lung count data not used in assessment.

Intake assessment table

Name	Intake (pCi)
Worker 110	4.7E4