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Approval:	Signature on File Daniel Mantooth, Document Owner	Approval Date:	10/12/2006
Approval:	Signature on File John M. Byrne, Task 3 Manager	Approval Date:	10/12/2006
Concurrence:	Signature on File Edward F. Maher, Task 5 Manager	Concurrence Date:	10/12/2006
Concurrence:	Signature on File Kate Kimpan, Project Director	Concurrence Date:	10/23/2006
Approval:	Brant A. Ulsh Signature on File for James W. Neton, Associate Director for Science	Approval Date:	10/25/2006

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/30/2004	00	New technical basis document for the Paducah Gaseous Diffusion Plant – Occupational Internal Dose. First approved issue. Initiated by Jay J. Maisler.
10/25/2006	01	Approved issue of Revision 01. This revision addresses the comment from the meeting with the United Steelworkers Local 5-550 and SPFPA Local 111 held on 2/10/2005. Constitutes a total rewrite of document. Incorporates recent direction from NIOSH to include DOL review comments on page 5. Revisions address corrective actions responding to OCAS assessment and internal review comments from Task 5. Changes were made at the end of Section 5.2. The original Table 5-3 has been deleted and replaced with an expansion of the original Table 5-4, which becomes Table 5-3. Table 5-2 has been updated to reflect new Table numbers. Incorporates internal and NIOSH formal review comments. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Daniel Mantooth.

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ACRONYMS AND ABBREVIATIONS

AMAD	activity median aerodynamic diameter
Bq	becquerel
dpm	disintegrations per minute
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
g	gram
hr	hour
KPA	kinetic phosphorescence analysis
L	liter
MDA	minimum detectable amount
MDC	minimum detectable concentration
mg	milligram
mL	milliliter
mo	month
nCi	nanocurie
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
pCi	picocurie
PGDP	Paducah Gaseous Diffusion Plant
Ppb	parts per billion
ppm	parts per million
RU	Recycled Uranium
TRU	transuranic
U.S.C.	United States Code
UF_6	uranium hexafluoride
UO_3	uranium trioxide
µCi	microcurie
µg	microgram
µm	micrometer

5.1 INTRODUCTION

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

In this document, the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

5.1.1 Purpose

This TBD provides technical data and other key information which will serve as the technical basis for evaluating internal occupational radiation dose for EEOICPA claimants who were employed at the Paducah Gaseous Diffusion Plant.

5.1.2 Scope

This document discusses the radionuclides potentially encountered by Paducah Gaseous Diffusion Plant (PGDP) employees during the Plant's operational history. The PGDP mission was to enrich uranium in the form of uranium hexafluoride (UF_6) from roughly 0.7% ^{235}U (natural enrichment) to around 3% ^{235}U for use in domestic and foreign power reactors (DOE 2000, p. 8). Enrichment operations began in 1952 in the first four process buildings, C-331, C-333, C-310, and C-315. From 1953 until 1977, UF_6 feed material was produced from uranium trioxide (UO_3) at the plant. From 1953 to 1964, and again from 1968 to 1977, UF_6 was produced from the recycled uranium (RU) produced from spent reactor fuel. In May 1977, the feed plants ceased operation and all feed to the enrichment process was in the form of UF_6 obtained from outside sources. Other chemical compounds of uranium were present throughout the Plant's history including UO_2F_2, UF_4, and UO_3.

ORAUT (2004a) contains detailed information on the history of PGDP and the feed conversion and enrichment process.

5.2 SOURCE TERM

The radionuclides potentially encountered by PGDP employees consist primarily of the isotopes of uranium, ^{238}U, ^{234}U, and ^{235}U. The progeny of dosimetric interest for these radionuclides includes ^{230}Th and ^{234m}Pa (BJC 1999, p. 8). While a range of ^{235}U enrichment values (from natural to 3%) was encountered in feed and product material, the dose reconstructor should assume a nominal enrichment value of 2% ^{235}U for all feed or product materials.

The presence of transuranic (TRU) and fission product isotopes has been known since the early days of operation (ORAUT 2004a). These radionuclides were present in small amounts in the feed material produced from RU, and include ^{237}Np, ^{239}Pu, and ^{241}Am. Technetium-99 is the fission product of concern from a dosimetry standpoint. During the conversion of the feed material from UO_3 to UF_6, the elemental species of the TRU and fission products react differently from a chemical standpoint. For example, ^{99}Tc tends to form a very volatile fluoride; readily introduced into the enrichment cascade, it essentially follows the UF_6 to the surge and/or product station. On the other hand, both ^{241}Am and ^{239}Pu form essentially nonvolatile fluorides. Most of these isotopes will remain in the feed conversion byproducts (i.e., ash) or in the feed cylinder heels, a primary source of TRU exposure from this process. Some ^{241}Am will appear in the cascade components as a result of the decay of ^{241}Pu. While ^{237}Np forms a volatile fluoride, it rapidly oxidizes and plates on the metal cylinder walls (PACE and University of Utah 2000, p. 26), so the main hazard from this isotope is related to cylinder cleaning operations and cascade component maintenance. PGDP conducted operations to recover ^{99}Tc (April 1960 through June 1963) and ^{237}Np (November 1958 through March 1962), which presents an increased potential to exposure from these isotopes.

Table 5-1 lists information on the isotopic species associated with PGDP operations and facilities and their dates of operation (when available).

5.2.1 Isotopic Concentrations

At PGDP, monitoring for intakes of uranium, *in vivo* or *in vitro*, often resulted in reports of elemental uranium concentration in urine or the mass of elemental uranium in organs or the whole

Table 5-1. Radiological source term for PGDP processes and facilities.

Building	Process	Dates[a]	Radionuclides of concern[b]	Absorption type[c]
C-360	Product shipping and transfer		U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Tc-99	F M M, S F
C-400	Converter maintenance Converter salvage CIP/CUP Phase 1 CIP/CUP Phase 2	4/53–Present 9/54–6/61 3/73–9/81	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 99-Tc	F M M, S F
C-400/ C-710	^{237}Np recovery ^{99}Tc recovery	11/58–3/62 4/60–6/63	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 99-Tc	F M M, S F
C-409	Converter refurbish	1973–1981	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Tc-99	F M M, S F
C-410	Green salt production UF_6 production ^{99}Tc /^{237}Np recovery (MgF_2)	1953–1956 1953–Present 9/61–6/63	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 99-Tc Th-230 Am-241	F, M, S M M, S F S M
C-420	Green Salt Production	1956–1977	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Tc-99 Th-230 Am-241	F, M, S M M, S F S M
C-331	Cascade ops/maintenance	9/52–Present	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Tc-99	F M M, S F
C-333	Cascade ops/maintenance	9/52–Present		
C-335	Cascade ops/maintenance	4/54–Present		
C-337	Cascade ops/maintenance	7/54–Present		
C-310	Surge and product ^{99}Tc /^{237}Np recovery (MgF_2)	9/52–Present 1/63–6/63	U-234, 235, 236, 238 Np-237 Pu-238, -239, -240, -242 Tc-99 Th-230	F M M, S F S
C-315	Surge and waste	9/52–Present	U-234, -235, -236, -238 Th-230	F S
C-340	Metal production	12/57–12/62 1/68–10/77	U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Th-230	M, S M M, S S

Table 5-1 (Continued). Radiological source term for various PGDP processes and facilities.

Building	Process	Dates[a]	Radionuclides of concern[b,c]	Absorption type[b,c]
C-720	Maintenance		U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Tc-99 Th-230 Am-241	F, M, S M M, S F S M
C-746	Waste metal smelting		U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Th-230	M, S M M, S S
C-749	Uranium metal burial		U-234, -235, -236, -238 Np-237 Pu-238, -239, -240, -242 Th-230	M, S M M, S S

a. All dates are from DOE (2000) except those for C-409 and the Cascade Ops/Maintenance buildings, which are from PACE and University of Utah (2000) and ORAUT (2004a), respectively.
b. From Hill and Strom (1993, Table 16.2).
c. From BJC (1999, Table 1.7)

body. However, the internal dose assessment process requires the use of isotopic concentrations as input. As stated above, the chemical properties of the TRU and fission product contaminants resulted in changes in their relative concentrations in different parts of the process when compared to the original feed material. This section provides bounding estimates for radionuclide concentrations. The concentrations relative to the mass of total uranium and the activity of total uranium are shown in Tables 5-2 and 5-2a, respectively. A summary discussion on the information presented in the tables and its derivation is provide below. Details of units conversion and data sources can be found in Barton (2006).

Pre-1983 Operations

Column 1, Pulverizer, Ash, Green Salt C-410; Column2, Converter Salvage

The values presented in Columns 1 and 2 are taken from PACE and University of Utah (2000) Table 7.9. The maximum air concentration data was used to provide bounding values for TRU concentrations. The data in Table 7.9 is in units of uCi/cc which were converted to the desired units of pCi (TRU)/g (U) or pCi (TRU)/pCi(U). Details of this process can be found in Barton (2006).

The maximum plutonium activity in air is reported in PACE and the University of Utah (2000) as being comprised of ^{239}Pu. However, it is more consistent with all references (BJC[2000], Hightower et al [200]) to assume that the faction of the alpha activity attributed to ^{239}Pu be considered as total alpha-emitting isotopes plus ^{241}Am. A nominal isotopic distribution for TRU in fuel-grade plutonium provided in ORAUT (2005) was used to calculate the ratios of the various isotopes from the value provided in the reference.

Column 1 values are applicable to feed material production operations in C-410/C-420. Column 2 values are applicable to converter maintenance/salvage and cylinder cleaning operations in C-400.

Column 4, Tc/Np Recovery Operations; Column 5, Balance of Plant

The values in Column 4 and Column 5 are taken from BJC (2000), Table 2.4.1. This reference presents a detailed analysis of the mass balance of ^{239}Pu, and ^{237}Np using individual activity analysis. Table 2.4.1 presents the maximum concentrations (in ppb) of the ^{239}Pu and ^{237}Np for the various processes encountered at PGDP. The remaining plutonium isotopes and ^{241}Am concentrations are determined using the isotopic rations for fuel grade plutonium found it ORAUT (2005) and as described above.

The values in Column 4 are applicable to all Tc/Np recovery operations in C-400, **including those that may have taken place after 1983.**

The values for Column 5 consist of the upper 95% bound of the average Table 2.41 values (minus those areas/processes already accounted for in Columns 1 and 2). They are applicable to pre-1983 activities which include Cascade Operations (C-333, C-337, C-410), Production/Handling UF_4 (C-340), Connecting/Disconnecting UF_6 tails Cylinders (C-315, C-340), Connecting/Disconnecting Product Cylinders (C-310), Changing/Cleaning MgF_2 Traps (C-410, C-310), and U Metal Production (C-340) BJC (2000), Table 2.4.1.

Post-1983 Operations

Column 3, Converter Salvage; Column 6, Balance of Plant

Converter Salvage (Column 3) and converter salvage operations (Column 6) are based on Hightower et al. (2000). These values were included in the TBD to account for the fact that an insignificantly small percentage (.008% of the total) of RU feed was introduced to the cascade after 1977 (BJC 2000, Appendix C). In addition, a two-phase (1954 to 1961 and 1973 to 1981) upgrade program effectively replaced the major components of the cascade. These facts would imply that, over time, TRU and fission product contaminants would be greatly reduced from the process, with the exception of those entrained in the feed and tail cylinder heels. Only cylinder maintenance/washing operations would have a potential for exposure to these isotopes. Hightower et al (2000) contain analytical data in ppb for ^{237}Np, ^{239}Pu, and ^{241}Am in depleted uranium cylinders and feed material. The values in Table 3, the bounding concentrations for UF_6 feed, were used to represent Converter Salvage Operations (Column 3). As in the case for the Pre-1983 operations, these include converter maintenance/salvage and cylinder cleaning in C-400. The values for the remaining plutonium isotopes were determined as using the ratios in ORAUT (2005), as described above.

For Balance of Plant Operations (Column 6) ^{239}Pu, ^{237}Np, and ^{241}Am values specified in Hightower et al (2000) Table 2 were used. These data represent the concentrations of dispersed contamination in DUF_6 cylinders and, considering the negligible quantity of RU introduced to the plant during this period, is believed to bound the actual ^{239}Pu and ^{237}Np levels since these isotopes were primarily concentrated in the pulverizer ash or plated within feed cylinder walls.

Column 6 is applicable to post-1983 activities which include Cascade Operations (C-333, C-337, C-410), Production/Handling UF_4 (C-340), Connecting/Disconnecting UF_6 tails Cylinders (C-315, C-340), Connecting/Disconnecting Product Cylinders (C-310), Changing/Cleaning MgF_2 Traps (C-410, C-310), and U Metal Production (C-340) BJC (2000), Table 2.4.1.

Thorium 230 (^{230}Th)

Pace and University of Utah (2000) list ^{230}Th, a decay product of uranium as a potential source of concern and provide estimates for the activity concentration in Buildings C-400 and C-410 (Columns 1 and 2 of Table 5-2 and 5-2a. BJC (2000) and Hightower et al (2000) offer no data on ^{230}Th. The ratio of Np-237 to Pu-239 data from each BJC (2000) Table 2.4.1 and Hightower et al (2000) was compared to the same ratio determined for the PACE "mixes". The mix for which the two ratios compared most closely was used to determine the ^{230}Th concentration. A detailed discussion of this technique is provided in Barton (2006).

Technetium 99 (^{99}Tc)

The ^{99}Tc concentration for all operations except ^{99}Tc recovery is assumed to remain constant throughout the process and is based on the reported 7-ppb maximum for the feed material (Smith 1984). The ^{99}Tc concentration for recovery operations is from BJC (2000).

Note: If the work location of a claimant is unknown, use Columns 2 or 3 in Table 5-2 (or Table 5-2a), as appropriate to the times of employment.

Table 5-2. Bounding isotopic contributions in PGDP operations (pCi/g).

Table 5-2. Bounding isotopic contributions in PGDP operations (pCi/g U).

Radionuclide	1 Pulverizer, ash handling, green salt C-410 Pre-1983[a]	2 Converter Salvage Line Pre-1983[a]	3 Converter Salvage Line Post-1983[b]	4 Tc/Np recovery Operations, C-400[c]	5 Balance of plant Pre-1983[c]	6 Balance of plant Post-1983[b]
Np-237	3.55E+04	1.61E+06	3.81E+04	1.76E+07	1.67E+03	3.67E+00
Pu-239/240	9.00E+05	3.24E+04	7.09E+04	4.42E+06	4.11E+01	1.95E+00
Pu-238	1.94E+05	7.01E+03	1.53E+04	9.54E+05	8.89E+00	4.21E-01
Pu-242	4.46E+01	1.61E+00	3.52E+00	2.19E+02	2.04E-03	9.67E-05
Pu-241	3.51E+07	1.27E+06	2.76E+06	1.72E+08	1.61E+03	3.38E-01
Am-241	1.56E+05	5.62E+03	1.85E+03	7.65E+05	7.13E+00	4.21E+00
Th-230	1.18E+06	1.67E+05	3.64E+05	2.27E+07	2.11E+02	1.00E+01
Tc-99	1.20E+05	1.20E+05	1.20E+05	3.81E+07	1.20E+05	1.20E+05
U-234	6.81E+05	6.81E+05	6.81E+05	6.81E+05	6.81E+05	6.81E+05
U-235	4.27E+04	4.27E+04	4.27E+04	4.27E+04	4.27E+04	4.27E+04
U-238	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05	3.27E+05
U-236	9.00E+02	9.00E+02	9.00E+02	9.00E+02	9.00E+02	9.00E+02

a. PACE and University of Utah (2000)
b. Hightower et al (2000)
c. BJC (2000)

Table 5-2a. Bounding isotopic contributions in PGDP operations (pCi/pCi U)[a].

Radionuclide	1 Pulverizer, ash handling, green salt C-410 Pre-1983[a]	2 Converter Salvage Line Pre-1983[a]	3 Converter Salvage Line Post-1983[b]	4 Tc/Np recovery Operations, C-400[c]	5 Balance of plant Pre-1983[c]	6 Balance of plant Post-1983[b]
Np-237	3.38E-02	1.53E+00	3.63E-02	1.67E+01	1.59E-03	3.49E-06
Pu-239/240	8.56E-01	3.08E-02	6.75E-02	4.21E+00	3.91E-05	1.86E-06
Pu-238	1.85E-01	6.67E-03	1.46E-02	9.08E-01	8.46E-06	4.01E-07
Pu-242	4.24E-05	1.53E-06	3.35E-06	2.08E-04	1.94E-09	9.20E-11
Pu-241	3.34E+01	1.21E+00	2.63E+00	1.64E+02	1.53E-03	3.22E-07
Am-241	1.48E-01	5.35E-03	1.76E-03	7.28E-01	6.79E-06	4.01E-06
Th-230	1.12E+00	1.59E-01	3.46E-01	2.16E+01	2.01E-04	9.52E-06
Tc-99	1.14E-01	1.14E-01	1.14E-01	3.63E+01	1.14E-01	1.14E-01
U-234	4.88E-01	4.88E-01	4.88E-01	4.88E-01	4.88E-01	4.88E-01
U-235	2.17E-02	2.17E-02	2.17E-02	2.17E-02	2.17E-02	2.17E-02
U-238	4.88E-01	4.88E-01	4.88E-01	4.88E-01	4.88E-01	4.88E-01
U-236	1.31E-03	1.31E-03	1.31E-03	1.31E-03	1.31E-03	1.31E-03

a. Table 5-2 converted from pCi/g U (2% enriched) to pCi/pCi U (Natural). Conservative assumption when U basis by weight is 2% enriched since the activity is higher, however when U activity basis is used, the lower specific activity of natural Uranium should be used.

When determining potential intakes of TRU/^{99}Tc by applying the isotopic ratios presented in Table 5-2 to urinalysis data, dose reconstructors should consider that PACE and University of Utah (2000) noted instances where the bioassay data in the electronic database are not consistent with original documents. Verify urinalysis results obtained from the electronic database against the written records.

5.3 *IN VITRO* MEASUREMENT METHODS

From the start of Plant operations in 1952, samples of urine from workers involved in enrichment operations were analyzed for uranium.[2] Over time, other workers were included in the monitoring program. In addition, special sampling occurred in response to incidents or issues (i.e., assessments of the radiological impacts of TRU elements and technetium); however, those analytical methods were typically performed off the PGDP site, at ORNL during early periods and later at analytical services contractor locations. Table 5-3 lists sampling frequencies and volumes for workers assigned to specific buildings during various periods. In addition, the table provides default values if the specific location of a claimant is not available.

At PGDP, routine urine samples were typically single voids collected during the middle of the week. Each could have been measured for specific gravity, pH, sugar, and albumin levels, as well as for uranium content. During the early years, total uranium concentrations were measured using a calibrated fluorimeter with a detection level of 0.005 mg/L (PACE and University of Utah 2000, p. 40).

[2] Fecal sampling was occasionally performed for special studies. However, a program for routine or diagnostic monitoring of fecal samples was never implemented.

In later years, total uranium content was assessed by kinetic phosphorescence analysis (KPA). Neither methodology included isotopic determinations.

Table 5-3. *In vitro* measurement frequencies.[a, b]

Period	Facility	Frequency	Volume
1953 to present	C-310	Every 4 weeks	Spot
1953 to present	C-315	Every 4 weeks	Spot
1953 to present	C-340	Every 4 weeks	Spot
1953 to present	C-400	Every 4 weeks	Spot
1953 to present	C-410	Every 4 weeks	Spot
1953 to present	Remainder	Yearly	Spot
1959 to present	All	Within 0.5 hr of incident	Spot
1960	C-410	Every 2 mo	Spot
1960	C-340	Every 3 mo	Spot
1960	C-331, C-333, C-335, C-337	Every 4 mo	Spot
1960	C-410	Every 6 mo	Spot
1991 to present	All	Every 4 weeks	24-hr collection or simulated 24-hr collection
Default	N.A.	Every 4 weeks	Spot

a. Sources: PACE and University of Utah (2000, Section 7.4); Author unknown (no date 1).
b. There is evidence that in 1960 the measurement frequency for Building C-410 and C-340 workers could have been either every 4 weeks or every 2 mo (C-410) or 4 mo (C-340). However, there is no referenceable indication whether there was a special class of worker to which the 2-mo frequency applied. The overlapping values have been left in the table.

5.3.1 Measurement Types and Detection Levels

Table 5-4 lists the *in vitro* measurement types and detection levels during various periods. For samples analyzed at the site, the detection level for total uranium in urine was reported as 0.005 mg/L (PACE and University of Utah 2000, Section 4.2.1). If detection levels for specific methods were not found in the available references, levels specified as typical in ICRP (1989) were used.

In addition, if it is not clear from the monitoring records how or where a particular claimant's sample was analyzed, assume that they were analyzed in-house (i.e., at PGDP) and use the MDC from that measurement type to assess missed dose. Finally, if a record contains a notation of "less than X micrograms/L" or "< x pCi/sample", that value should reflect the MDC for that sample.

5.3.2 Reporting Formats and Codes

A variety of codes occurs on various urine bioassay records for PGDP. Table 5-5 summarizes those known at the date of this report, along with their interpretations.

5.4 *IN VIVO* MEASUREMENT METHODS

Whole-body counting and other *in vivo* methods were implemented beginning in the early 1950s. Until the present (2003), this measurement method was used primarily in response to incidents, or for assessing the magnitude of insoluble material intakes. Even when routine whole-body counting was instituted for certain PGDP employees in the late 1960s, the counting frequency was sporadic and seldom greater than once per year.

Table 5-4. *In vitro* measurement types and detection levels for various periods.[a]

Period	Measurement type	Radionuclide	MDC[a]	Comments
1952–1961	PGDP fluorimetry[b]	Total uranium	5 µg/L	
1962–1976	PGDP fluorimetry	Total uranium	5 µg/L	
1962–1976	PGDP fluorimetry	Total uranium	5 µg/L	
1962–1969	PGDP fluorimetry	Total uranium	5 µg/L	
1977–1982	PGDP fluorimetry	Total uranium	5 µg/L	
1982–present				
1985–1989	ORNL[d]	U-234, -235, and -238	0.03 pCi/sample	
1989–present	ORNL	U-234, -235, and -238	0.01 pCi/sample	
1989–present	Contractor[e]	U-234, -235, and -238	0.3 pCi/L	
1999-Present	KPA[c]	Total uranium	0.06µg/sample	DR should use the cite MDA for all urinalysis results by KPA, regardless of analysis date
1999–present	ORNL	Natural uranium	0.06 mg/sample	
1969–1985	PGDP gross beta[c]	Tc-99	10 dpm/ml	10 dpm/mL
1985–1989	ORNL	Isotopic plutonium	0.02 pCi/sample	
1989–present	ORNL	Isotopic plutonium	0.01 pCi/sample	
1985–1989	ORNL beta counting	Tc-99	18.1 pCi/sample	
1989–present	ORNL	Tc-99	90.9 pCi/sample	
1999–present	ORNL	Th-228, -230, and -232	0.014 pCi/sample	
1985 to 1989	ORNL	Np-237	0.04 pCi/sample	
1989–present	ORNL	Np-237	0.01 pCi/sample	
1985–1989	ORNL	Pu-238, -239, and -240	0.02 pCi/sample	
1989–present	ORNL	Pu-238, -239, and -240	0.01 pCi/sample	
1985–1989	ORNL	Am-241	0.02 pCi/sample	
1989–present	ORNL	Am-241	0.01 pCi/sample	

a. MDC = minimum detectable concentration.
b. PACE and University of Utah (2000, p. 40).
c. BJC (1999), Table 3.9
d. ORAUT (2004b).
e. ICRP (1989).

5.4.1 Measurement Types and Detection Levels

At PGDP, whole-body counting was performed using a mobile counter provided by the Y-12 Plant (sometimes referred to as the MMES Counter) and at other facilities. Table 5-6 lists general information about the detection capabilities of this counting system for various periods.

5.4.2 Reporting Formats and Codes

A variety of codes and reporting formats appear in the *in vivo* bioassay records. Table 5-7 lists the known codes with their interpretations.

5.4.3 Instructions for Addressing Possible Interferences and Uncertainties

On occasion, *in vivo* measurement results included ^{137}Cs. However, those PGDP workers could have had body burdens of ^{137}Cs from nonoccupational sources (e.g., fallout and consumption of specific foodstuffs). There is no evidence of occupational intakes of ^{137}Cs at PGDP, so no dose of record should be associated with these measurement results, if any.

5.4.4 Assessment of Intake for Monitored Employees

In general, available urine results should be considered the primary method of dose reconstruction. *In vivo* measurements, especially in the earlier years of operation, were not used for routine monitoring purposes. However, those results might be useful for verifying assessments of dose based on urine

Table 5-5. *In vitro* record codes.[a,b,c,d]

Form identifier	Measurement type	Column identifier	Code	Interpretation
WCP-455	Urine bioassay	Reason for Visit	33, 35	Industrial health recheck
WCP-455	Urine bioassay	Reason for Visit	OB, 39, 35-1	Recall sample requested following elevated sample
WCP-455	Urine bioassay	Reason for Visit	MM recall	Monday morning recall sample; requested after days off work
WCP-455	Urine bioassay	Reason for Visit	32, 33, Term	Termination samples
WCP-455	Urine bioassay	Reason for Visit	30, 22	Rehire
WCP-455	Urine bioassay	Reason for Visit	37, 18, Per.	Periodic physical; confirmatory samples were collected during routine physicals; this typically did not pertain to those on routine monitoring program.
WCP-455	Urine bioassay	Reason for Visit	26	Preemployment
WCP-455	Urine bioassay	Reason for Visit	005, 07, 60, Exposure, Special, Release	Samples collected following exposure or potential exposure in uranium release or spill
WCP-455	Urine bioassay	Bottle No.		Permanent sample number
PGDP_HISTORICAL_URINE	Urine bioassay	Results		There is no distinction between positive results and detection limits.
PGDP_HISTORICAL_URINE	Urine bioassay	Sample Type	Physical	Routine physicals included collection of bioassay sample (random sampling program); this typically did not pertain to those on routine monitoring program.
WCP-455	Urine bioassay	Reason for Visit	I.H.R. or IHR	Industrial health recheck (associated with routine physicals)
WCP-455	Urine bioassay	Top of Card	“A”	Refers to shift worked (“A” = day shift)
WCP-455	Urine bioassay	Top of Card	“B”	Refers to shift worked (“B” = evening shift)
WCP-455	Urine bioassay	Top of Card	“O”	Refers to shift worked (“O” = midnight shift)
WCP-455	Urine bioassay	F, HG and OTHER	“B” (128)	Indicates shift and hours worked
PGDP_ANALIS_URINE	Urine bioassay	Results		Results are given in µg/L.
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	4	dpm/L
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	1	dpm/ml
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	2	dpm/day
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	3	dpm/sample
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	5	µg/ml
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	6	Bq/L
5EA HPINT - Bioassay Results Report	Urine bioassay	Units	7	Bq/day
5EA HPINT - Bioassay Results Report	Urine bioassay	Reason	3	Routine
5EA HPINT - Bioassay Results Report	Fecal analysis	Units	3	dpm/sample
5EA HPINT - Bioassay Results Report	Fecal analysis	Units	7	Bq/day

Table 5-5 (Continued). *In vitro* record codes.[a,b,c,d]

Form identifier	Measurement type	Column identifier	Code	Interpretation
5EA HPINT - Bioassay Results Report	Breath analysis	Units	2	dpm/day
5EA HPINT - Bioassay Results Report	Breath analysis	Units	3	dpm/sample
5EA HPINT - Bioassay Results Report	Breath analysis	Units	4	dpm/L
5EA HPINT - Bioassay Results Report	Breath analysis	Units	6	Bq/L
5EA HPINT - Bioassay Results Report	Breath analysis	Units	7	Bq/day
WCP-885	Urine bioassay	Schedule	A	Day sample is to be taken (1=Monday; 2=Tuesday; 3=Wednesday; 4=Thursday)
WCP-885	Urine bioassay	Schedule	B	Type analysis (1=Uranium; 2=Fluoride; 3=Mercury)
WCP-885	Urine bioassay	Location	Shifts	A, B, O and D
			Frequency	Uranium #1 = 1 a month; Fluoride #2 = 1 a year; Mercury #3 = Blank
Permanent log (sample collection log)	Urine bioassay	Number	Permanent sample number	Numbers are consecutive from top to bottom of page and continue from one page to next.
IBM Report Cards	Urine bioassay		A	Name
IBM Report Cards	Urine bioassay		B	Badge
IBM Report Cards	Urine bioassay		C	Date (date shown on log)
IBM Report Cards	Urine bioassay		D	Code for this service
IBM Report Cards	Urine bioassay		E	Analysis results in boxes labeled Uranium, Fluorides, and Mercury
UCN-5242, “Sample Analysis (Medical).”	Urine bioassay	Same as for NCP-455	Same as for NCP-455	This form number was in use from 1969 to 1970.

a. Sources: Maisler (2003); Eckerman and Ward (1992); Author unknown (no date 1)
b. Form WCP-885 is referred to as “NCP-885” in Eckerman and Ward (1992); however, they appear to identify the same form.
c. Around June 1956, form WCP-455 was modified with additional columns added. Individual bioassay records reviewed indicates the exact date the newly expanded form was used. This varies a little from person to person, but was in the middle of 1956 for all records reviewed.
d. The bioassay records we have starting in 1977 (exact dates vary from person to person) are not copies of results recorded on bioassay cards; they are database printouts (e.g., “PGDP_Historical_Urine”). The uranium results are in units of µg/L with results recorded to the nearest integer, i.e., 0, 1, 2, etc.

Table 5-6. *In vivo* measurement types and detection levels for various periods.

Period	Equipment	Measurement type	Radionuclide	MDA[a] (units of record)	Action level for recount	Action level for work restriction
1958	ORNL[b]	Lung	Pu-238	80 nCi	Not specified	Not specified
1960–1967	Y-12[c]	Whole body	Np-237	2.7 nCi	Not specified	Not specified
1968–1980	Y-12 mobile counter[d]	Whole body	U-235	0.083 mg	Not specified	Not specified
1968–1980	Y-12 mobile counter[d]	Whole body	U-238	4 mg	Not specified	Not specified
1968–1980	Y-12 mobile counter[d]	Whole body	Np-237	17,000 pCi	Not specified	Not specified
1965–1991	Y-12 mobile counter[d]	Lung	Total uranium	4 mg	4 mg	27 mg
1965–1991	Y-12 mobile counter[d]	Lung	Enriched uranium (2% ^{235}U)	0.1 mg	0.1 mg	0.24 mg
1965–1991	Y-12 mobile counter[d]	Lung	Depleted uranium	4 mg	4 mg	37 mg
1965–1991	Y-12 mobile counter[e]	Lung	Np-237	200 pCi	1,700 pCi	17,000 pCi
1991–1995	Helgeson counter[d]	Lung	Total uranium	2 – 4 mg	2 – 4 mg	27 mg
1991–1995	Helgeson counter[d]	Lung	Enriched uranium	0.04 – 0.07 mg	0.04 – 0.07 mg	0.24 mg
>1995	No counting performed					

a. MDA = minimum detectable activity or amount. The MDAs shown for uranium, while given in units of mass, are presumed to have been based on measurement of Th-234 activities along with an assumed isotopic ratio. It is presumed that the results for enriched uranium are based on measurement of U-235 activities and an assumption of enrichment. However, these presumptions cannot be confirmed so cautious use of these MDA values is recommended.
b. ORAUT (2004b)
c. ORAUT (2006)
d. ORAUT (2004c)
e. Hill and Strom (1993)

bioassay results, in determining likely absorption types, or in providing upper and lower limits to the range of possible doses.

5.5 SIGNIFICANT INCIDENTS WITH INTERNAL DOSE POTENTIAL

During operations at PGDP, a number of incidents occurred that increased the potential for intakes of radioactive materials. If a claimant (or employee) recalls involvement in one or more of those incidents, dose reconstructors can use the information in Table 5-8 to identify the dates, location, and/or source term for an incident-specific dose assessment.

Table 5-7. *In vivo* record codes.[a]

Form identifier	Measurement type	Column identifier	Code	Interpretation
In Vivo Radiation Monitoring Report	Whole-body count	Surface contamination	Check mark, yes	Surface contamination on the subject was checked. If measurable activity was found, it was so noted on card.
In Vivo Radiation Monitoring Report	Whole-body count	Analysis Sequence		These align with Output - Analysis Sequence Results listed at bottom of card; they are not relevant to dose reconstruction process.
In Vivo Radiation Monitoring Report	Whole-body count	Output - Analysis Sequence Results	A. Enriched Uranium	The maximum U-235 enrichment was 2% until 2000, after which it was 5%.
In Vivo Radiation Monitoring Report	Whole-body count	Output - Analysis Sequence Results	J. NLO Uranium	Refers to special spectrum region of interest for National Lead of Ohio, early operator of Fernald facility.
In Vivo Radiation Monitoring Report	Whole-body count	Hand-written notes	No Np noted	Presence or absence of Np-237 was qualitatively evaluated.
In Vivo Radiation Monitoring Report (with boxes for data entry)	Whole-body count	Hand-written notes	BFD	Initials of whole-body counter operator (individual who filled out the card)
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	M	µCi
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	N	nCi
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	P	pCi
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	D	dpm
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	B	Bq
5EA HPINT - Bioassay Results Report	*In vivo* records	Units	U	µg

[a] Sources: Maisler (2003); Eckerman and Ward (1992); Author unknown (no date 1).

Table 5-8. A history of significant incidents and events.[a]

Incident date	Incident description	Facility	Other information
1952–1990	Exposure to UF_4, UO, and process dust during guard patrolling	All buildings	
1952–1980	Exposure to uranium metal		
July 1953	First use of reactor tails		
November 1956	Fire	C-310	
1957–1977	Green salt, black oxides on floors and other surfaces	C-340	
December 1962	Fire	C-337	
March 1962	Explosion and fire	C-340	One fatality
April 1968	Worker overexposure	Unknown	Two workers overexposed
January 1978	Fire	C-315	
1958 to 1962	Cascade improvement program	C-331, C-333, C-335, and C-337	
1974 to 1982	Cascade improvement program	C-331, C-333, C-335, and C-337	
	Neptunium production	C-400	
1980 to 1982	Exposure to UF_4 and uranium dust during drum crushing	C-746	

a. Source: PACE and University of Utah (2000).

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GLOSSARY

absorption type

Categories for materials according to their speed of absorption in the body, which replaced the earlier inhalation clearance classes. Defined by the International Commission on Radiological Protection, the absorption types are F for fast absorption (formerly inhalation class D), M for moderate absorption (formerly inhalation class W), and S for slow absorption (formerly inhalation class Y). Also called solubility type.

activity median aerodynamic diameter (AMAD)

Diameter of a unit density sphere with the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol. In relation to health physics, normally assumed to be 5 micrometers.

bioassay

Determination of kinds, quantities, or concentrations, and in some cases locations of radioactive material in a living body, whether by direct measurement (*in vivo* measurement) or by analysis and evaluation of materials excreted or removed from the body (*in vitro* measurement).

body burden

Amount of radioactive material in an individual's body at a particular point in time.

dose

In general, the effects of ionizing radiation in terms of the specific amount of energy absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays. Various terms narrow the type of dose, and some are additive:

- Absorbed dose is the amount of energy deposited in a substance by ionizing radiation.
- Collective dose is the sum of the doses to a specific population.
- Committed dose is the dose over time (usually 50 years for workers) to a specific organ or tissue from an intake of radioactive material.
- Cumulative dose is the sum of all doses to the same portion of the body or to the whole body over time.
- Deep dose is the dose at a 1-centimeter depth in tissue (1,000 milligrams per square centimeter).
- Effective dose is the sum of the equivalent doses in the principal tissues and organs of the body, each weighted by a tissue weighting factor that accounts for the probabilities of fatal and nonfatal cancers according to severity and the average length of life lost due to an induced cancer. It indicates the biological effect of the radiation exposure in that tissue.
- Equivalent dose or dose equivalent is the absorbed dose in a tissue or organ multiplied by a weighting factor for the particular type of radiation.

- Organ dose is the dose to a specific organ.
- Penetrating dose is that from higher energy photon (gamma and X-ray) radiation and neutron radiation that penetrates the outer layers of the skin. Nonpenetrating dose is that from beta and lower energy photon radiation.
- Personal dose equivalent is the dose equivalent in soft tissue below a specified point on the body at a specified depth.
- Shallow dose is the dose at a 0.07-centimeter depth in tissue (7 milligrams per square centimeter).
- Skin dose is the dose to the skin.
- Whole-body dose is the dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder.

dose equivalent (*H*, DE)
Product of absorbed dose in units of rem or sievert in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose. See *dose*.

exposure
(1) In general, the act of being exposed to ionizing radiation. See *acute exposure* and *chronic exposure*. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens. In this document, exposure does not refer to the radiological physics concept of charge liberated per unit mass of air.

insoluble material
A term loosely used to describe the relative degree of solubility of a material in body fluids. Recognizing that no material is absolutely insoluble, the terms low solubility or poorly soluble are preferable.

intake
Radioactive material taken into the body by inhalation, absorption through the skin, injection, ingestion, or through wounds. Depending on the radionuclide involved, intakes are in units of mass, activity, or potential alpha energy.

internal dose or exposure
Dose received from radioactive material in the body.

internal dose assessment
Estimation of an intake of radioactive material and the consequent internal radiation dose based on measurements in the work environment and/or bioassay.

in vitro
Of or relating to a process that takes place under artificial conditions or outside a living organism (e.g., in the laboratory). From Latin meaning *in glass*.

in vivo
Of or relating to a process that takes place in a living organism. From Latin meaning *in life*.

lung solubility type
See *absorption type*.

minimum detectable amount (MDA)
Lowest amount of radioactive activity or substance amount detectable by a specific instrument or process. Smallest amount or activity of a radionuclide in a sample or organ that yields a result above the detection level with a specific probability of a Type II (false negative) error while accepting an specific probability of a Type I (false positive) error.

minimum detectable concentration (MDC)
Lowest concentration of a material in a substance (e.g., urine) detectable by a specific instrument or process. Minimum detectable activity (or amount) in units of concentration.

minimum reporting level
Level below which an analytical dose is not recorded in the worker's dose record, usually based on a site-specific policy decision. The recording level is not necessarily the same as the minimum detectable amount or activity for that measurement. Also called less-than value, minimum reportable dose, minimum recordable or recording dose, recording level, and reporting level.

monitoring (personnel)
Periodic or continuous determination of the presence or amount of ionizing radiation or radioactive contamination in air, surface water, groundwater, soil, sediment, equipment surfaces, or personnel (for example, bioassay or alpha scans). In relation to personnel, monitoring includes internal and external dosimetry including interpretation of the measurements.

occupational dose
Internal and external ionizing radiation dose from exposure during employment. Occupational dose does not include that from background radiation or medical diagnostics, research, or treatment.

radiation
Subatomic particles and electromagnetic rays (photons) that travel from one point to another, some of which can pass through or partly through solid materials including the human body. Radiation, as used in this document, does not include nonionizing radiation, such as radio- or microwaves, or visible, infrared, or ultraviolet light.

reactor tails
Recycled uranium (typically UO_3) from reactor operations (typically Savannah River and Hanford) that contains traces of transuranic isotopes not removed during chemical processing (e.g., reduction-oxidation).

recording level
See *minimum reporting level*.

rem
Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The average American receives 360 millirem a year from background radiation. The

sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

routine monitoring
Monitoring carried out at regular intervals during normal operations.

sievert (Sv)
International System unit for dose equivalent, which indicates the biological damage caused by radiation. The unit is the radiation value in gray (equal to 1 joule per kilogram) multiplied by a weighting factor for the type of radiation and a weighting factor for the tissue; 1 Sv equals 100 rem.

special monitoring
Monitoring in addition to the routine monitoring program carried out for special purposes such as estimating the amount of radionuclide deposited in a person after a known or suspected accidental intake or after a known or suspected environmental release.

spot sample
In relation to bioassay, usually a single void of urine.