SEC Petition Evaluation Report
Petition SEC-00057-2

Report Rev #: 0 Report Submittal Date: September 7, 2007

Subject Expert(s):	James Berger, Tim Adler
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Petition Administrative Summary

Petition Under Evaluation

Petition #	Petition Type	Petition B Qualification Date	DOE/AWE Facility Name
SEC-00057-2	83.13	November 21, 2006	Hanford

Petitioner Class Definition

All employees in all facilities and areas of the Hanford Nuclear Reservation from January 1, 1942 through December 31, 1990.

Proposed Class Definition

All employees of the Department of Energy (DOE), its predecessor agencies, and DOE contractors or subcontractors, who were monitored, or should have been monitored for:

1. internal thorium radiological exposures from September 1, 1946 through December 31, 1959 in the following facilities in the 300 Area: the Metal Fabrication Building (313), the Reactor Fuel Manufacturing Pilot Plant (306), the 300 Area Maintenance Shops (3722), and the Radiochemistry Laboratory (3706); or
2. internal americium radiological exposures from January 1, 1949 through December 31, 1968 in the following areas: the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z),

while working at the Hanford Nuclear Reservation for a number of work days aggregating at least 250 work days, or in combination with work days within the parameters established for one or more other classes of employees in the SEC (excluding aggregate work day requirements).

Related Petition Summary Information

SEC Petition Tracking #(s)	Petition Type	DOE/AWE Facility Name	Petition Status
SEC-00078	83.13	Hanford	Merged with SEC-00057

Related Evaluation Report Information

Report Title	DOE/AWE Facility Name
SEC-00057-1, 1st Part of this Evaluation Report	Hanford

ORAU Lead Technical Evaluator: Albert W. Wolff	**ORAU Review Completed By:** Michael Kubiak

Peer Review Completed By:	[Signature on file] *Sam Glover*	09/07/2007 *Date*
SEC Petition Evaluation Reviewed By:	[Signature on file] *J. W. Neton*	09/10/2007 *Date*
SEC Evaluation Approved By:	[Signature on file] *Larry Elliott*	09/11/2007 *Date*

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Evaluation Report Summary: SEC-00057-2, Hanford

This evaluation report by the National Institute for Occupational Safety and Health (NIOSH) addresses a class of employees proposed for addition to the Special Exposure Cohort (SEC) per the *Energy Employees Occupational Illness Compensation Program Act of 2000*, as amended, 42 U.S.C. § 7384 *et seq.* (EEOICPA) and 42 C.F.R. pt. 83, *Procedures for Designating Classes of Employees as Members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000*.

Petitioner-Requested Class Definition

This evaluation reviews the requested classes as follows:

- Petition SEC-00057, qualified on November 21, 2006, requested that NIOSH consider the following class: *All employees in all facilities and areas of the Hanford Reservation from January 1, 1942 through December 31, 1990.*

- Petition SEC-00078, qualified on February 8, 2007, requested that NIOSH consider the following class: *All roving maintenance carpenters and apprentice carpenters that worked in the 100, 200, 300, and 400 Areas of Hanford from April 25, 1967 through February 1, 1971.*

NIOSH-Proposed Class Definition

NIOSH merged the two petitions because the class requested in SEC-00078 is encompassed by the class requested in SEC-00057. For evaluation purposes, due to the complexity of Hanford operations over almost fifty years, the SEC-00057 class and associated evaluation report were divided into two separate time periods.

A previous evaluation report, SEC-00057-1, evaluated the SEC-00057 petitioner-requested years during which the Hanford site was being constructed and initially operated by the DuPont Company (October 1, 1943 through August 31, 1946).

This report, SEC-00057-2, evaluates Hanford site operations from September 1, 1946 through December 31, 1990, and defines a single class of employees for which NIOSH has determined it cannot estimate radiation doses with sufficient accuracy as follows:

1. internal thorium radiological exposures from September 1, 1946 through December 31, 1959 in the following facilities in the 300 Area: the Metal Fabrication Building (313), the Reactor Fuel Manufacturing Pilot Plant (306), the 300 Area Maintenance Shops (3722), and the Radiochemistry Laboratory (3706); or
2. internal americium radiological exposures from January 1, 1949 through December 31, 1968 in the following areas: the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z),

while working at the Hanford Nuclear Reservation for a number of work days aggregating at least 250 work days, or in combination with work days within the parameters established for one or more other classes of employees in the SEC (excluding aggregate work day requirements).

Feasibility of Dose Reconstruction

Per EEOICPA and 42 C.F.R. § 83.13(c)(1), NIOSH has established that it does not have access to sufficient information to: (1) estimate the maximum radiation dose, for every type of cancer for which radiation doses are reconstructed, that could have been incurred in plausible circumstances by any member of the class; or (2) estimate radiation doses more precisely than a maximum dose estimate. Information available is not sufficient to document or estimate the maximum internal and external potential exposure to members of the proposed class under plausible circumstances during the specified period.

Health Endangerment Determination

Per EEOICPA and 42 C.F.R. § 83.13(c)(3), a health endangerment determination is required because NIOSH has determined that it does not have sufficient information to estimate dose for the members of the proposed class.

NIOSH did not identify any evidence supplied by the petitioners or from other resources that would establish that the proposed class was exposed to radiation during a discrete incident likely to have involved exceptionally high-level exposures. However, evidence indicates that some workers in the proposed class may have accumulated substantial chronic exposures through episodic intakes of radionuclides, combined with external exposures to gamma, beta, and neutron radiation. Consequently, NIOSH has determined that health was endangered for those workers covered by this evaluation who were employed for at least 250 aggregated work days either solely under their employment or in combination with work days within the parameters established for other SEC classes (excluding aggregate work day requirements).

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SEC Petition Evaluation Report for SEC-00057-2

ATTRIBUTION AND ANNOTATION: This is a single-author document. All conclusions drawn from the data presented in this evaluation were made by the ORAU Team Lead Technical Evaluator: Albert W. Wolff, Oak Ridge Associated Universities. These conclusions were peer-reviewed by the individuals listed on the cover page. The rationales for all conclusions in this document are explained in the associated text.

1.0 Purpose and Scope

This report evaluates the feasibility of reconstructing doses for external or internal radiation exposures while working at the Hanford Nuclear Reservation from September 1, 1946 through December 31, 1990.

It provides information and analyses germane to considering a petition for adding a class of employees to the congressionally-created SEC.

This report does not make any determinations concerning the feasibility of dose reconstruction that necessarily apply to any individual energy employee who might require a dose reconstruction from NIOSH. This report also does not contain the final determination as to whether the proposed class will be added to the SEC (see Section 2.0).

This evaluation was conducted in accordance with the requirements of EEOICPA, 42 C.F.R. pt. 83, and the guidance contained in the Office of Compensation Analysis and Support's (OCAS) *Internal Procedures for the Evaluation of Special Exposure Cohort Petitions*, OCAS-PR-004.

2.0 Introduction

Both EEOICPA and 42 C.F.R. pt. 83 require NIOSH to evaluate qualified petitions requesting that the Department of Health and Human Services (HHS) add a class of employees to the SEC. The evaluation is intended to provide a fair, science-based determination of whether it is feasible to estimate with sufficient accuracy the radiation doses of the class of employees through NIOSH dose reconstructions.[1]

42 C.F.R. § 83.13(c)(1) states: *Radiation doses can be estimated with sufficient accuracy if NIOSH has established that it has access to sufficient information to estimate the maximum radiation dose, for every type of cancer for which radiation doses are reconstructed, that could have been incurred in plausible circumstances by any member of the class, or if NIOSH has established that it has access to sufficient information to estimate the radiation doses of members of the class more precisely than an estimate of the maximum radiation dose.*

[1] NIOSH dose reconstructions under EEOICPA are performed using the methods promulgated under 42 C.F.R. pt. 82 and the detailed implementation guidelines available at http://www.cdc.gov/niosh/ocas.

Under 42 C.F.R. § 83.13(c)(3), if it is not feasible to estimate with sufficient accuracy radiation doses for members of the class, then NIOSH must determine that there is a reasonable likelihood that such radiation doses may have endangered the health of members of the class. The regulation requires NIOSH to assume that any duration of unprotected exposure may have endangered the health of members of a class when it has been established that the class may have been exposed to radiation during a discrete incident likely to have involved levels of exposure similarly high to those occurring during nuclear criticality incidents. If the occurrence of such an exceptionally high-level exposure has not been established, then NIOSH is required to specify that health was endangered for those workers who were employed for at least 250 aggregated work days within the parameters established for the class or in combination with work days within the parameters established for other SEC classes (excluding aggregate work day requirements).

NIOSH is required to document its evaluation in a report, and to do so, relies upon both its own dose reconstruction expertise as well as technical support from its contractor, Oak Ridge Associated Universities (ORAU). Once completed, NIOSH provides the report to both the petitioner(s) and to the Advisory Board on Radiation and Worker Health (Board). The Board will consider the NIOSH evaluation report, together with the petition, petitioner(s) comments, and other information the Board considers appropriate, in order to make recommendations to the Secretary of HHS on whether or not to add one or more classes of employees to the SEC. Once NIOSH has received and considered the advice of the Board, the Director of NIOSH will propose a decision on behalf of HHS. The Secretary of HHS will make the final decision, taking into account the NIOSH evaluation, the advice of the Board, and the proposed decision issued by NIOSH. As part of this decision process, petitioners may seek a review of certain types of final decisions issued by the Secretary of HHS.[2]

3.0 Petitioner-Requested Class/Basis & NIOSH-Proposed Class/Basis

This petition reviews the requested classes as follows:

- Petition SEC-00057, qualified on November 21, 2006, requested that NIOSH consider the following class: *All employees in all facilities and areas of the Hanford Reservation from January 1, 1942 to December 31, 1990.*

- Petition SEC-00078, qualified on February 8, 2007, requested that NIOSH consider the following class: *All roving maintenance carpenters and apprentice carpenters that worked in the 100, 200, 300, and 400 Areas of Hanford from April 25, 1967 through February 1, 1971.*

The petitioners provided information and affidavit statements in support of the petitioners' belief that accurate dose reconstruction over time is impossible for the Hanford workers in question. NIOSH deemed the following information and affidavit statements sufficient to qualify SEC-00057 and SEC-00078 for evaluation:

> The SEC-00057 petitioner claimed that personal monitoring data gaps existed for several of the individual workers listed in the petition. NIOSH found that the monitoring gap

[2] See 42 C.F.R. pt. 83 for a full description of the procedures summarized here. Additional internal procedures are available at http://www.cdc.gov/niosh/ocas.

information provided by the petitioner did not support the submission basis for qualifying the petition. However, during the qualifying process, NIOSH identified some early (prior to 1949) operational periods for which no internal exposure monitoring was performed or was reliable. NIOSH qualified SEC-00057 on this basis.

The SEC-00078 petitioner provided several examples of work performed by construction trades workers that took place in contaminated areas or with contaminated equipment that sometimes required respiratory protection devices. The petitioner asserted that no bioassay monitoring or *in vivo* measurements were extended to the roving carpenter working class and no internal monitoring results could be found in their exposure records. The petitioner also provided the abstract of a peer-reviewed journal article claiming that of the 33,459 workers who were employed for at least 180 days and that had at least one annual external dosimetry report, annual external dosimetry records were missing for 8% of the years of employment, which corresponds to 32,323 missing annual external dosimetry records (Richardson, 1999).

The information and statements provided by the petitioners qualified the petition for further consideration by NIOSH, the Board, and HHS. The details of the petition basis are addressed in Section 7.4.

NIOSH merged the two petitions because the class requested in SEC-00078 is encompassed by the class requested in SEC-00057. For evaluation purposes, due to the complexity of Hanford operations over almost fifty years, the SEC-00057 class and associated evaluation report were divided into two separate time periods.

A previous evaluation report, SEC-00057-1, evaluated the petitioner-requested years during which the Hanford site was being constructed and initially operated by the DuPont Company (October 1, 1943 through August 31, 1946).

In this report, NIOSH evaluates the years of Hanford site operations from September 1, 1946 through December 31, 1990. The start date for Evaluation Report SEC-00057-2 follows directly after the dates covered in the SEC-00057-1 Evaluation Report. Based on its research, NIOSH identified and defined a single class of employees for which NIOSH cannot estimate radiation doses with sufficient accuracy. The class for this report, for which NIOSH cannot estimate radiation doses with sufficient accuracy, is defined as: All employees of the Department of Energy (DOE), its predecessor agencies, and DOE contractors or subcontractors, who were monitored, or should have been monitored for:

1. internal thorium radiological exposures from September 1, 1946 through December 31, 1959 in the following facilities in the 300 Area: the Metal Fabrication Building (313), the Reactor Fuel Manufacturing Pilot Plant (306), the 300 Area Maintenance Shops (3722), and the Radiochemistry Laboratory (3706); or
2. internal americium radiological exposures from January 1, 1949 through December 31, 1968 in the following areas: the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z),

while working at the Hanford Nuclear Reservation for a number of work days aggregating at least 250 work days, or in combination with work days within the parameters established for one or more other classes of employees in the SEC (excluding aggregate work day requirements).

A previous evaluation report, SEC-00057-1, evaluated the petitioner-requested years during which the Hanford site was being constructed and initially operated by the DuPont Company (October 1, 1943 through August 31, 1946). The start date for this evaluation report, SEC-00057-2, follows directly after the dates covered by that evaluation.

4.0 Data Sources Reviewed by NIOSH

NIOSH identified and reviewed numerous data sources to locate information relevant to determining the feasibility of dose reconstruction for the class of employees proposed for this petition. This included determining the availability of information on personal monitoring, area monitoring, industrial processes, and radiation source materials. The following subsections summarize the data sources identified and reviewed by NIOSH.

4.1 Site Profile Technical Basis Documents (TBDs)

A Site Profile provides specific information concerning the documentation of historical practices at the specified site. Dose reconstructors can use the Site Profile to evaluate internal and external dosimetry data for monitored and unmonitored workers, and to supplement, or substitute for, individual monitoring data. A Site Profile consists of an Introduction and five Technical Basis Documents (TBDs) that provide process history information, information on personal and area monitoring, radiation source descriptions, and references to primary documents relevant to the radiological operations at the site. The Site Profile for a small site may consist of a single document. As part of NIOSH's evaluation detailed herein, it examined the following TBDs for insights into Hanford operations or related topics/operations at other sites:

- *Technical Basis Document for the Hanford Site – Introduction*, ORAUT-TKBS-0006-1; Rev. 03; May 23, 2007; SRDB Ref ID: 31874

- *Technical Basis Document for the Hanford Site – Site Description*, ORAUT-TKBS-0006-2; Rev. 01; May 17, 2007; SRDB Ref ID: 31859

- *Technical Basis Document for the Hanford Site – Occupational Medical Dose*, ORAUT-TKBS-0006-3; Rev. 01; April 11, 2005; SRDB Ref ID: 19491

- *Technical Basis Document for the Hanford Site – Occupational Environmental Dose*, ORAUT-TKBS-0006-4; Rev. 02; June 5, 2007; SRDB Ref ID: 32073

- *Technical Basis Document for the Hanford Site – Occupational Internal Dose*, ORAUT-TKBS-0006-5; Rev. 02; June 22, 2007; SRDB Ref ID: 32522

- *Technical Basis Document for the Hanford Site – Occupational External Dose*, ORAUT-TKBS-0006-6; Rev. 03; June 5, 2007; SRDB Ref ID: 32074

4.2 ORAU Technical Information Bulletins (OTIBs) and Procedures

An ORAU Technical Information Bulletin (OTIB) is a general working document that provides guidance for preparing dose reconstructions at particular sites or categories of sites. An ORAU Procedure provides specific requirements and guidance regarding EEOICPA project-level activities, including preparation of dose reconstructions at particular sites or categories of sites. NIOSH reviewed the following OTIBs and procedures as part of its evaluation:

- *OTIB: Estimating the Maximum Plausible Dose to Workers at Atomic Weapons Employer Facilities*, ORAUT-OTIB-0004; Rev. 03, PC-2; December 6, 2006; SRDB Ref ID:29949

- *OTIB: External Coworker Dosimetry Data for the Hanford Site*, ORAUT-OTIB-0030; Rev. 00 PC-1; November 7, 2006; SRDB Ref ID: 29961

- *OTIB: Internal Coworker Dosimetry Data for the Hanford Site*, ORAUT-OTIB-0039; Rev. 00 PC-2; January 31, 2007; SRDB Ref ID: 29969

- *OTIB: Parameters to Consider When Processing Claims for Construction Trade Workers,* ORAUT-OTIB-0052; Rev. 00, PC-1; January 16, 2007; SRDB Ref ID: 29978

- *OTIB: Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses,* ORAUT-OTIB-0054; Rev. 00; May 11, 2007; SRDB Ref ID: 31780

- PROC: *Occupational Onsite Ambient Dose Reconstruction for DOE Sites*, ORAUT-PROC-0060, Rev. 01; June 28, 2006; SRDB Ref ID: 29986

- PROC: *Occupational X-Ray Dose Reconstruction for DOE Sites*, ORAUT-PROC-0061, Rev. 01; July 21, 2006; SRDB Ref ID: 29987

4.3 Facility Employees and Experts

NIOSH conducted interviews with former Hanford employees to obtain input regarding health physics practices, internal and external dosimetry programs, dose recording practices, and radiological incidents. In-person interviews were conducted both individually and in group settings.

The personal interviews generally focused on the employees' area of expertise while at Hanford, and general health physics monitoring practices. Most of these interviews were conducted with individuals that were expected to have first-hand knowledge regarding external monitoring decisions and methods, the response of external monitoring devices, and areas where significant neutron exposures were expected. With the exception of one interview in March 2007, all of the interviews were conducted June through August of 2007. All interviewees indicated that employees who entered radiologically controlled areas wore external dose monitoring devices. In general, those interviewed thought that photon monitoring during this period was reasonably accurate, but that the neutron monitoring capabilities were poor.

There were two group interviews that included individuals from a variety of disciplines. They were conducted on June 18 and June 19, 2007. Approximately 40 employees attended each group interview. They provided input regarding external monitoring practices, various radiological incidents, and recordkeeping. External monitoring, in general, was thought to be consistently applied. However, there was concern that specific incidents resulted in missed dose for certain individuals. Some of the incidents described could affect individual dose reconstructions; however, the incidents could not be reasonably applied to a specific class of workers. Several employees offered input regarding logbooks or similar reporting tools that could be useful for providing details regarding work practices and incidents.

In general, information obtained through the interviews with former employees and facility experts was consistent with that found in NIOSH documents regarding the Hanford facility.

4.4 Previous Dose Reconstructions

NIOSH reviewed its NIOSH OCAS Claims Tracking System (NOCTS) to locate EEOICPA-related dose reconstructions that might provide information relevant to the petition evaluation. Table 4-1 summarizes the results of this review for the period of September 1, 1946 through December 31, 1990. (NOCTS data available as of August 9, 2007)

Table 4-1: No. of Hanford Claims Submitted Under the Dose Reconstruction Rule
(September 1, 1946 through December 31, 1990)

Description	Totals
Total number of claims submitted for dose reconstruction	2,564
Number of dose reconstructions completed	1,827
Number of claims for which internal dosimetry records were obtained for the identified years in the proposed class definition	1,919
Number of claims for which external dosimetry records were obtained for the identified years in the proposed class definition	2,370

NIOSH reviewed each claim to determine whether internal and/or external personal monitoring records could be obtained for the employee. The Computer Assisted Telephone Interviews (CATI) provided some information that is useful for dose reconstruction, including work locations, hours worked, incidents (such as fires, radioactive releases, and spills), and hazards encountered. Of the 2,564 claims submitted, 75% have internal monitoring data available and 92% have external monitoring data available. As of August 9, 2007, 50 recent claims had not yet received a response from DOE for exposure records.

4.5 NIOSH Site Research Database

NIOSH also examined its Site Research Database to locate documents supporting the evaluation of the proposed class. One thousand thirty-two documents (as of August 16, 2007) in this database were identified as pertaining to Hanford. These documents were evaluated for their relevance to this petition. The documents include historical background on process descriptions, the radiological controls program, site history, monthly reports, incident documentation, and epidemiological studies.

4.6 Other Technical Sources

- *Radiation Protection Criteria and Standards: Their Basis and Use*; H. M. Parker; SRDB Ref ID: 27678

- *Hanford Declassified Document Retrieval System (DDRS)*; A DOE project that provides access to declassified information including that declassified in response to Freedom of Information Act (FOIA) requests; Available at http://www2.hanford.gov/declass/

- *U. S. Department of Energy OpenNet System*; OpenNet provides access to recently declassified documents, including information declassified in response to Freedom of Information Act (FOIA) requests; Available at https://www.osti.gov/opennet/

- *Comprehensive Epidemiologic Data Resource (CEDR) Database*

- *Hanford Radiological Exposure (REX) Database*

4.7 Documentation and/or Affidavits Provided by Petitioners

In qualifying and evaluating the petition, NIOSH reviewed the following documents submitted by the petitioners:

Petition SEC-00057:

- *Potential Unrecorded Neutron Dose*, Letter to distribution; Jack J. Fix; August 27, 1997; OSA Ref ID: 100318, page 23-25

- *Review of NIOSH Site Profile for the Hanford Site,* SCA-TR-TASK1-0004; Richland, Washington, Contract No. 200-2004-03805, Task Order No. 1; June 10, 2005, OSA Ref ID: 100304, page 38-43

- *Vern Haugen's Handwritten Diary*; June 2006; OSA Ref ID: 100318, page 62-77

- *Twelve affidavits submitted by the SEC-00057 petitioner regarding missing dosimetry records, location of records, medical conditions of individual workers, incidents, and overexposures*; OSA Ref ID: 100318

Petition SEC-00078:

- *The Release of Radioactive Materials from Hanford: 1944 through 1972*, Washington State Dept. of Health: Hanford Health Info Network; OSA Ref ID: 100102

- *Ionizing Radiation and Mortality Among Hanford Workers: Completed NIOSH Initiated Research*, Summary (unknown source) of NIOSH-initiated research (no date); OSA Ref ID: 102415

- *Hanford Site: A Guide to Record Series Supporting Epidemiologic Studies Conducted for the Department of Energy*; U.S. Department of Energy; OSA Ref ID: 100101, pages 3-22

- *Review of NIOSH Site Profile for the Hanford Site,* SCA-TR-TASK1-0004; S. Cohen & Associates; June 10, 2005, OSA Ref ID: 100101, pages 23-244

- *Draft Issue Resolution Matrix,* Based on the SC&A Review of the NIOSH Site Profile for the Hanford Site; OSA Ref ID: 100105, pages 71-72

- *NIOSH Health Hazard Evaluation Report,* HETA 2004-0145-2941; CH2M Hill Hanford Group, Inc. and U.S. Department of Energy, Office of River Protection Richland, Washington; July 2004; OSA Ref ID: 100105, pages 73-100

- *US Admits Radiation Exposure Killed Nuclear Weapons Workers*; Kate Randall, World Socialist Web Site; February 2, 2000; OSA Ref ID: 102414, pages 4-5

- *Missing Annual External Radiation Dosimetry Data Among Hanford Workers*; D. Richardson, S. Wing, J. Watson, and S. Wolf; Journal of Exposure Analysis and Environmental Epidemiology, 9:575-585; 1999; [Journal name recently changed to "Journal of Exposure Science and Environmental Epidemiology"]; OSA Ref ID: 102416, page 2

- *NIOSH Assessment of Information Needed for the Evaluation of the Health Effects Due to Occupational Exposures for DOE Site Remediation Workers*; National Institute for Occupational Safety and Health (NIOSH); January 2001; OSA Ref ID: 102417, pages 4-5

- *Affidavit from Petitioner of the Hanford Carpenters/Carpenter Apprentices Part B SEC Petition*; an affidavit from the petitioner describing seven incidents occurring at Hanford to the proposed class, and two accidents occurring to the petitioner; OSA Ref ID: 102410

5.0 Radiological Operations Relevant to the Proposed Class

Unless otherwise indicated, information for Section 5.0 is from three sources: *History of the Plutonium Production Facilities at the Hanford Site Historic District, 1943-1990* (DOE, 2002); *A History of Major Hanford Facilities and Processes Involving Radioactive Material* (Ballinger, 1991); and *Manhattan Project Buildings and Facilities at the Hanford Site: A Construction History* (Gerber, 1993).

The following subsections summarize both radiological operations at Hanford from September 1, 1946 through December 31, 1990 and the information available to NIOSH to characterize particular processes and radioactive source materials. From available sources NIOSH has gathered process and source descriptions, information regarding the identity and quantities of each radionuclide of concern, and information describing both processes through which radiation exposures may have occurred and the physical environment in which they may have occurred. The information included within this evaluation report is intended only to be a summary of the available information. Radiological operations are discussed in more detail in Section 5.2.

5.1 Hanford Plant and Process Descriptions

In 1943, the U.S. Army Corp of Engineers selected an area of approximately 600 square miles in southeastern Washington State for the production of plutonium and other nuclear materials to support weapons production for World War II. This area, now known as the Hanford site, was divided into three major operational areas, each located and designed specifically for its role in plutonium production. The 100 Areas handled production reactor operations; the 200 Areas handled fuel reprocessing, plutonium recovery, and waste management; and the 300 Area handled fuel fabrication and general research and development activities. In the early 1970s, operations began in another area—the 400 Area, about 6 miles northwest of the 300 Area. The facility at this location was an experimental sodium-cooled breeder reactor known as the Fast Flux Test Facility. There were other Hanford Areas, but they had little, if any, involvement with radioactive materials operations. The 600 Area was the general category assigned to facilities that supported multiple operations but were not within the security boundaries of other major areas. The 600 Area included road systems, fire stations, environmental and weather monitoring stations, and Nike missile sites. Some 300 Area waste disposal sites and Buildings 213-J and 213-K (plutonium nitrate paste and contaminated sodium storage) were also included in the 600 Area. The 700 Area was located inside the community of Richland, Washington, and consisted of administration, central supply, laundry, and repair/maintenance services. Richland Village was designated as the 1100 Area and the Richland Construction Camp was the 3000 Area. Figure 5-1 shows the locations of the major Hanford operational areas.

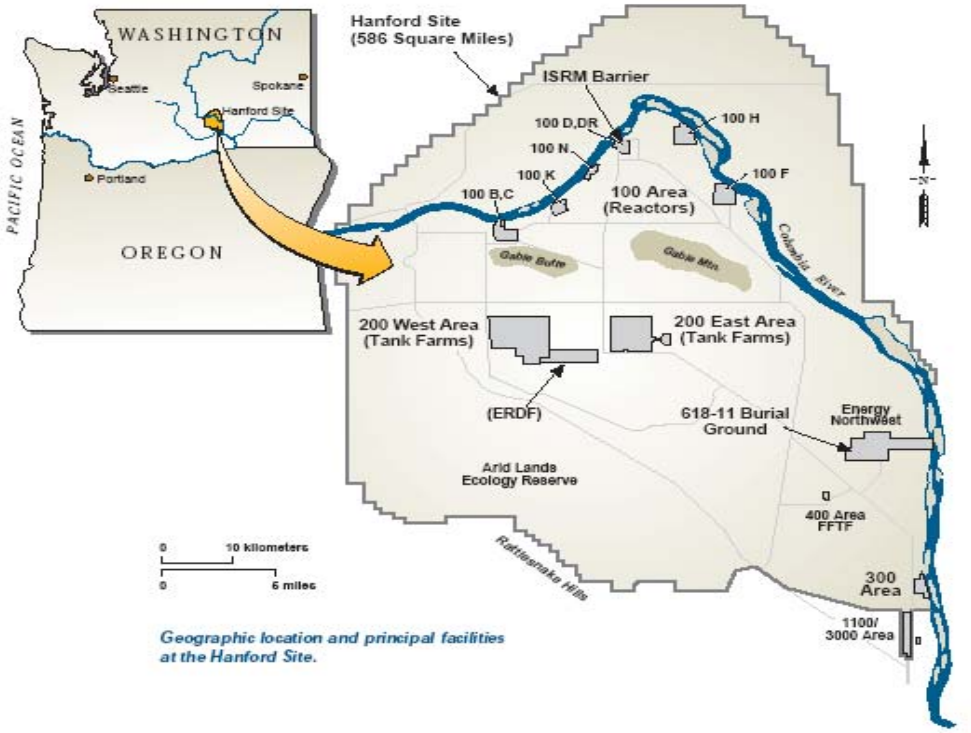


Figure 5-1: Hanford Site Major Operational Areas

To ensure continuing plutonium production capacity in case of maintenance downtime, emergencies, and/or sabotage, many major Hanford plutonium production operations were duplicated. In addition, Hanford plutonium production operations were also essentially self-sufficient, containing all necessary support services and facilities. However, both initially and with changing missions, some operations utilized facilities and services located in other Areas. For example, after 1973 most of the radioactive liquid waste from all Hanford operations was transferred to the 200 Areas for processing and storage.

Construction of facilities for plutonium production began almost immediately in 1943 and production operations were underway by the end of 1944. In 1944 and 1945, additional facilities were constructed to increase production and research and development (R&D). During the late 1940s and the 1950s, additional production capacity and R&D facilities were added. Plutonium production at the Hanford site peaked from 1956 through 1965. During the late 1960s, plutonium needs decreased and many production facilities were shut down. Initial decommissioning of many production-related facilities began in the late 1960s and continued through 1990. In 1988, the final Separations Plant (PUREX) and the Plutonium Finishing Plant were shut down. As production operations decreased, the era of diversification began; Hanford site activities related to peaceful applications of nuclear energy replaced those related to weapons. The N Reactor was converted into a commercial power generator in 1963 and operated until 1987.

Table 5-1 summarizes Hanford site development.

Table 5-1: Hanford Site Development Chronology Table 5-1 spans two pages		
Dates	**Areas**	**Activities**
Pre-September 1946	All	Fuel manufacturing (313 and 314), reactors (100-B, 100-D, and 100-F), and separation/finishing (221/224-T, 221/224-B, 221/224-U, and 231-Z) facilities completed and operating; ongoing R&D activities related to reactors, radiation effects, and radiochemistry
August 1, 1946	All	Atomic Energy Act passed
September 1, 1946	All	General Electric Company assumes prime site contractor responsibility from E.I. DuPont de Nemours and Company
January 1, 1947	All	Manhattan Engineer Project replaced by Atomic Energy Commission
1947	All	Cold War Era begins
1947 - 1949	200	Installation of 42 single-shell waste tanks
1949	200	Startup of REDOX separations (C-Plant) and Rubber Glove (RG) Line in 231-Z Plutonium Finishing Plant
1949	100	Startup of H Reactor
1950 - 1952	200	Installation of 18 single-shell waste tanks
1950	100	Startup of DR Reactor
1951	200	Startup of 242-T and 242-B evaporators
1952	300	Startup of Physical Constants Test Reactor
1952	200	Startup of REDOX (S-Plant), U-Plant uranium recovery operations, and Remote A Line
1952	100	Startup of C Reactor, Experimental Animal Farm, and Aquatic Biology Laboratory
1953 - 1955	200	Installation of 21 single-shell waste tanks
1954	300	Startup of Thermal Test Reactor
1954	100	Startup of KW Reactor
1955	100	Startup of KE Reactor
1956	200	Shutdown of B-Plant and T-Plant; Startup of Uranium Trioxide Plant and PUREX (A-Plant)
1958	200	Shutdown of U-Plant
1960	300	Startup of Plutonium Recycle Test Reactor
1963 - 1964	200	Installation of 4 single-shell waste tanks
1964	100	Startup of N-Reactor power generating plant; Shutdown of DR Reactor
1964	200	Startup of Plutonium Reclamation Facility
January 4, 1965	All	Battelle Memorial Institute assumes responsibility for management of Hanford Site laboratories
November 1, 1965	100/300	Douglas-United Nuclear Inc. assumes responsibility for fuels and reactors
1965	100	Shutdown of H and F Reactors
January 1, 1966	200	ISOCHEM assumes responsibility for chemical processing and plutonium finishing
September 1, 1967	200	Atlantic Richfield Hanford Company assumes responsibility for chemical processing
1967	100	Shutdown of D Reactor
1967	300	Construction completed on High Temperature Lattice Test Reactor
1967	200	Shutdown of S-Plant (REDOX)
1968 - 1988	200	Installation of 28 double-shell waste tanks
1968	100	Shutdown of B Reactor
1969	100	Shutdown of C Reactor
1970	100	Shutdown of KW Reactor

Table 5-1: Hanford Site Development Chronology Table 5-1 spans two pages		
Dates	**Areas**	**Activities**
1971	100	Shutdown of KE Reactor
1972	200	Shutdown of Uranium Trioxide Plant
1973 - 1976	200	Startup of evaporator plants 242-S and 242-A
January 19, 1975	All	Energy Research and Development Administration replaces Atomic Energy Commission
July 1, 1977	200	Rockwell Hanford Operations assumes responsibility for reprocessing
October 1, 1977	All	Department of Energy replaces Energy Research and Development Administration
1980	400	Startup of Fast Flux Test Facility
1983	200	Restart of Uranium Trioxide Plant
June 29, 1987	All	Westinghouse Hanford Company assumes responsibility for fuel manufacturing, reactor operations, chemical engineering, and waste management
1987	100	Shutdown of N Reactor
1988	200	Shutdown of A-Plant (PUREX)
1989	200	Shutdown of Plutonium Finishing Plant
1989	All	Cold War Era ends

5.2 Hanford Functional Areas

Hanford operations during the period of September 1, 1946 through December 31, 1990 included the following major functional areas:

- Fuel Fabrication
- Reactor Operations
- Chemical Separations
- Plutonium Finishing
- Research and Development
- Tank Farms and Waste Management

The primary mission of early Hanford operations was production of plutonium and other nuclear materials to support weapons production. Operations developed, changed, and expanded to satisfy changing U.S. defense needs and developing nuclear knowledge and technology.

5.2.1 Fuel Fabrication

Plutonium was produced by irradiating uranium metal fuel in the Hanford Site reactors. The fuel for these reactors was fabricated in the 300 Area. Billets of natural uranium metal were received from offsite and stored in the 303 Buildings, where they were inventoried and inspected. The billets were

then transferred to the Metal Extrusion Building (314), where they were preheated in a furnace and then passed through an extrusion press to extrude the uranium into rods. After the uranium was in rod form, the rods were heated in an argon atmosphere to drive off occluded gases. Rods were then straightened, if necessary. Extrusion operations ceased in 1948 and rolled rods were obtained for fabrication process feed from other sites until 1950, at which time Hanford began making its own rolled rod feed stock.

Uranium rods were transferred to the 313 Building, where they were cut to the desired length by turret lathe and machine-finished into slugs. Slugs were inspected and degreased in a nitric acid solution. They were then heated by immersion in molten baths and inserted into thin aluminum cans. The initial heating process was known as the triple-dip process and was employed until 1959, at which time it was replaced by the lead-dip process. After the uranium slug was inserted into the aluminum can, an aluminum cap was welded in place. Bonds and welds were inspected and tested. The finished fuel elements, measuring 1.5 inches in diameter and 8 inches in length, were inspected and tested in the 305 Building. The fuel elements were then transferred and stored in the 100 Areas, awaiting irradiation in reactors. Fabrication of aluminum-clad fuel elements was performed at Hanford from 1944 through 1971, using this process.

Aluminum-clad natural uranium fuel was used for the eight, single-pass reactors. The N reactor used a tube-in-tube design fuel element containing slightly enriched (0.95 to 1.25%) uranium with zirconium (zircoloy-2) cladding. Fabrication of these elements was performed in the 333 Building between 1961 and 1988. The major difference in the fabrication process from that of the aluminum-clad elements was that uranium billets and zircoloy cladding were assembled and covered with a protective copper silicon shell. The entire assembly was then heated in an electric furnace and extruded into tubes. Extruded fuel tubes were cut to length and the ends were machine-finished. The protective copper silicon jacket was then removed by dissolving it in hot nitric acid. Zircoloy-2 end caps were then attached; elements were inspected, tested, transferred, and stored at the 100 N Area, awaiting irradiation in the N reactor.

During the mid- to late-1960s, pellets of lithium aluminate were prepared in the 3722 Building. These pellets were clad in zircoloy-2 tubes and inserted into N reactor fuel elements for production of tritium.
In addition to the above fuel fabrication operations, the Fuel Element Pilot Plant (306 Building) was completed in 1956 and expanded in 1960 to assist in 313 Building operations and for development of manufacturing processes for single-pass fuel. The 306 Building housed a complete fuel element manufacturing line, with the exception of autoclaving inspections.

Chips, turnings, and other solid scrap uranium pieces were salvaged and pressed into briquettes. Liquids were settled and filtered to collect fines. Dusts and fines were oxidized in gas furnaces. These reclaimed uranium wastes were shipped offsite for recycling.

NIOSH-reviewed documents contained sparse mention of fires occurring during the fuel fabrication operations. However, based on the history of other fuel fabrication operations, which entailed extrusion and machining of uranium metal, it is likely that such fires were not uncommon occurrences.

5.2.2 Reactor Operations

As of September 1, 1946, the comparatively small 305-B reactor use to test graphite, slugs, and rods used in the production reactors and the three production reactors (B, D, and F) were operating to produce plutonium-239 by neutron irradiation of uranium-238 fuel elements. The design of these production reactors was a water-cooled, graphite moderated pile with boron control rods. A typical production reactor consisted of a large graphite block, approximately 36 feet x 36 feet x 28 feet, containing 2,004 horizontal tubes for aluminum-clad natural uranium fuel elements. The block was surrounded by 8 – 10 inches of iron and 40 – 80 inches of reinforced concrete shielding. The assembly contained multiple lines for cooling water and gas systems. Three additional production reactors (H, DR, and C) of like design began operating in October 1949, October 1950, and November 1952, respectively. Two slightly larger reactors (KE and KW), each with 3,220 fuel tubes, became operational in 1955.

The N Reactor was a dual-purpose facility. In addition to producing plutonium, the heat from the cooling water was used to produce electricity for commercial purposes. N Reactor included a closed-loop primary cooling system, heat exchangers for steam production, and a confinement system to limit the spread of radioactivity in the event of an accident. The N reactor had 1,003 fuel tubes and used slightly enriched uranium in zircoloy-2-clad fuel elements. N Reactor went critical in 1964 and began producing electricity in 1966. The Federal government operated the reactor, while a consortium of public and private utilities operated the electric-generating portions of the plant.

Production reactors were located in the 100 Areas along the Columbia River, which provided access to large volumes of cooling water and achieved maximum distance from populated areas. Each reactor was located in its own complex, occupied approximately 1 square mile, and was separated from other reactors by a relative distance of 1 to 3 miles to reduce the impact of possible malfunctions and sabotage. Reactors were located in Buildings 105, each of which measured approximately 250 feet x 230 feet x 95 feet high. Each 105 building included a control room, spent fuel discharge area, fuel storage, and associated handling equipment. With the exception of the N reactor, each reactor complex included approximately 30 support buildings and facilities and essentially operated independent of the others.

With a reactor in the shutdown state, fresh fuel elements were loaded (“charged”) into fuel tubes at the face of the graphite block. As new elements were introduced, irradiated elements were pushed out of the back of the block and fell into a pool of water. (About 25% of the fuel tubes were typically replaced at the same time.) Irradiated fuel elements were allowed to cool in the pool to reduce radiation levels; using remote handling tools, the irradiated fuel elements were then loaded, while under 20 feet of water, into large buckets (approximately 1000 pounds of fuel elements per bucket). After a further cooling period of 30 days, the buckets of spent fuel elements were transferred to the cooling basin, awaiting placement into shield casks and shipment to the 200 Areas for separation.

Each reactor complex included facilities for managing its own waste. Single-pass cooling water and bleed-off from the N reactor recirculating primary coolant water were pumped to retention basins. From those retention basins, the liquids were released into the River or into soil columns. There were designated sites for burial of solid radioactive waste.

Reactors had associated high levels of direct gamma and neutron radiation during operation and high gamma levels during shutdown conditions and spent fuel handling. There was the potential for worker exposures to surface contamination and airborne contamination, in particular from fuel element failures. According to site health physics documentation, reactor work areas were categorized into danger zones (i.e., red, yellow and blue), which were subject to worker access limitations. For example, Special Work Permits were required for worker entry into red category zones. Direct radiation monitoring was performed using fixed and portable systems and workers wore personal monitoring devices. In potentially-contaminated areas, personnel protective clothing was worn, air monitoring was performed, and contamination monitors were provided. In addition, there were restrictions on eating and smoking in radiologically-contaminated areas.

5.2.3 Chemical Separations

Irradiated fuel elements were transported in shielded casks by rail from the 100 (reactor) Areas to the Chemical Separation Plants in the 200 Areas. Before 1950, irradiated fuel elements were transported approximately halfway to the Separations Facilities, where they were stored for up to 40 days in cooling basins in lag (irradiated fuel slag) storage buildings (212-N, 212-P, and 212-R Buildings) to allow for decay of short-lived radionuclides. After cooling, the fuel elements were reloaded into the casks for the remainder of the journey. After 1950, use of the interim storage was discontinued and irradiated elements were transported directly from the reactors to the Separation Plants.

Two Separations Plants, called the T Plant and the B Plant were operational as of September 1946. Each Plant included a separations building (221 Building) and a reduction building (224 Building). These plants were large, rectangular reinforced concrete structures that consisted of a gallery area, containing piping, electrical, and operational facilities, and a process canyon, below which was located equipment for conducting the chemical separations. Plant dimensions were approximately 810 feet x 85 feet x 102 ft high (approximately 20 feet of the height was below grade); T Plant had an extra section, about 65 feet in length. As with other major production facilities at Hanford, each Chemical Separations Plant included all buildings and support services so as to function as a self-sufficient operation.

The plutonium chemical separations process used in the T and B Plants was known as the bismuth phosphate batch process. Three buckets of irradiated fuel elements were emptied into the dissolver tank in the 221 Building canyon, then the dissolver cell lid was replaced. A caustic solution was introduced into the tank and the aluminum cladding was dissolved from the fuel elements. After the decladded elements were rinsed, the fuel elements were dissolved in nitric acid. Bismuth phosphate was then added to precipitate plutonium as plutonium nitrate. Repeated steps of precipitation and centrifugation were performed to thoroughly separate the plutonium nitrate from uranium, fission products, and impurities. At this stage, the plutonium nitrate was in a batch of approximately 330 gallons. Next, this batch was transferred to Building 224 (Bulk Reduction), where the 330 gallons were concentrated to approximately 8 gallons of plutonium nitrate paste and further precipitations with hydrogen fluoride and lanthanum salts were performed to remove additional impurities. Finally, the plutonium nitrate paste was then transferred to the 221 Z Building for “finishing.”

Both the T and B Plants ended plutonium chemical separations in 1956. The T Plant went on to be used as a decontamination facility from 1958 into the 1990s. From 1968 through February of 1985, the B Plant was modified to remove strontium-90 and cesium-137 from liquid waste generated by

separation processes. The wastes were centrifuged to remove semi-solids containing primarily strontium-90. Phosphotungstic acid was added to the supernate, precipitating cesium-137, which was then separated by centrifuge. Strontium-90 was purified by solvent extraction, stripped into an aqueous stream, and isolated. Cesium-137 was purified by ion exchange. Both the purified strontium-90 and cesium-137 were transferred to the 225-B Building Waste Encapsulation Storage Facility, where they were converted to solids and encapsulated.

The U Plant, of the same general design as the T and B Plants, was also constructed prior to September 1946. Initially, the U Plant was used for training, decontamination, and repair of equipment from the T and B Plants, rather than for separation operations. In 1952, the 221-U Building was modified to recover uranium from the wastes from plutonium separations. Uranium-containing slurries, stored in 12, 75-foot diameter underground tanks were centrifuged. Then, solvent extraction was used to extract the uranium from the slurry using tri-butyl phosphate. Residual plutonium and fission products were scrubbed from the organic uranium with nitric acid. The 224-U Building was also modified in 1956 to convert recovered uranium to a solid state. The uranium arrived at the facility in the form of uranyl nitrate hexahydrate; boiling concentrated the liquid. Heating to 800^{o} F then oxidized the material into uranium trioxide.

Two additional Separations Plants were constructed later. The S Plant, or REDOX (reduction-oxidation) Plant, began operation in 1952. This plant was approximately 468 feet x 161 feet x 83 feet high and included a 132-foot-high silo. It also contained two parallel gallery areas with a central process canyon. The A Plant, or PUREX (plutonium-uranium extraction) Plant began operation in 1956. The PUREX Plant was approximately 1005 feet x 104 feet x 62 feet high and contained one gallery area and one process canyon. REDOX ceased operation in 1967 and PUREX was shut down in 1988.

The REDOX and PUREX continuous solvent extraction processes replaced the bismuth phosphate batch process in the 1950s. The REDOX process was more efficient than the bismuth phosphate batch process and produced uranium as a byproduct. The REDOX process was a gravity flow process. There were four main steps in the REDOX process: pre-cycle, partition, uranium cycle, and plutonium cycle. In pre-cycle, aluminum nitrate was added to the aqueous feed solution from the nitric acid dissolver, changing the valence of the uranium and plutonium. Hexone flowed through the aqueous stream and extracted the uranium and plutonium in an organic phase, leaving the fission products in the aqueous stream. The fission products were transferred to a waste tank and the plutonium and uranium were stripped back into the aqueous phase. Next, the partition phase was accomplished by placing the uranium and plutonium in the organic (hexone) phase and altering the plutonium's valence by adding ferrous sulfamate. The uranium and plutonium were then extracted separately in aqueous phases. In the uranium cycle, uranium was converted to the aqueous phase, extracted in hexone, and stripped from the organic phase; it was then sent to the 224-U Building for concentrating. The plutonium cycle once again changed the valence, by addition of sodium dichromate and nitric acid, and extracted the plutonium in hexone from remaining fission products. The plutonium was stripped back into the aqueous phase and concentrated. The concentrated plutonium nitrate was transferred to the Plutonium Finishing Plant 221-Z Building.

The PUREX process was similar to the REDOX process, except that it employed pulsed columns rather than gravity flow, and the organic solvent was tri-butyl phosphate instead of hexone. There were six main steps in the PUREX process: co-decontamination, partition, uranium cycle, plutonium

cycle, neptunium cycle, and N cell cycle. Fission products were removed in the co-decontamination step, leaving uranium, plutonium, and neptunium in the organic stream. In the partition step, plutonium was removed by stripping from the organic stream and then returned to the aqueous phase. The separated uranium and neptunium were also stripped from the organic to the aqueous stream in this step. Uranium was recovered in the uranium cycle, concentrated, and stored for processing at the Uranium-224 Uranium Trioxide Plant. There were two stages in the plutonium cycle step for separating and decontaminating the plutonium. Repeated extraction and stripping steps of the neptunium cycle separated and decontaminated the neptunium, which was then isolated by ion exchange. The N cell was the load-out area of the PUREX Plant (DOE, 2002). (Load-out refers to the transfer of the concentrated plutonium nitrate to the Plutonium Finishing Plant.)

Chemical separations were operations that entailed potentially high radiation exposures. Of particular note was the sampling of process solutions on the canyon decks of the T and B Plants. Direct gamma radiation levels were high and respirators were required. This source of exposures was eliminated in the REDOX and PUREX Plant designs, which provided remote sampling stations in the gallery areas. However, because sampling entries to canyon decks were not required, the building design did not provide the same level of shielding for the canyons as was present in the T and B Plants. Another chemical separations operation that involved potentially high radiation exposures was service and maintenance of the cranes, located in the canyons.

5.2.4 Plutonium Finishing

Plutonium nitrate solution from the 200 Area Chemical Separations Facilities was transferred to the 231-Z Plutonium Isolation building (also in the 200 Area). In this facility, the plutonium was separated from the nitrate solution by the addition of hydrogen peroxide. The plutonium was then dried and shipped to the Los Alamos site for conversion into metallic plutonium for weapons use. 231-Z Building operations were performed in large protective boxes, equipped with rubber gloves (known as the Rubber Glove (RG) Line). In mid-1949, a new facility, the Plutonium Finishing Plant (234-5Z Building), began operation. This new facility was capable of converting the plutonium to the metallic form of “buttons” and performing casting and machining into components. The 231-Z Building continued to be used for preparation of plutonium oxalate until 1956.

Initial production in the Plutonium Finishing Plant used a glove box line similar to that in the Plutonium Isolation Building. Continued requirements for increased plutonium production resulted in the installation of Remote Mechanical (RM) Lines, which incorporated automated equipment and significantly out-produced the RG Line. The RG Line provided limited scope operations until its shutdown in 1953. The Remote Mechanical A (RM A) Line began operation in 1952. It operated until 1984, and over its lifetime, it was continually upgraded and improved. During its later years, the RMA Line use was limited to producing oxides. The Remote Mechanical C (RMC) Line started operation in 1960 to augment RMA line production and was permanently shut down in May of 1989. While its early work was for federal programs, in 1960 Hanford also began processing plutonium for the commercial nuclear fuel industry. Commercial production reached a maximum of about 30% of the total production in 1968, and ceased entirely in 1978. Total finishing production for all lines ranged from 250 kg in 1949 to over 4,500 kg in 1965. Hanford plutonium finishing operations ended in May 1989.

The 234-5Z and 231-Z Buildings housed metallurgical and analytical laboratories to support plutonium finishing and uranium trioxide operations. The 231-Z laboratory operated from 1943 until 1953 and the 234-5Z laboratory operated from 1949 through 1990.

Facilities were designed to recover and recycle plutonium from separations and finishing operations. The major recovery and recycle efforts were RECUPLEX, 232-Z Incinerator, 242-Z Waste Treatment Facility, and 236-Z Plutonium Reclamation Facility. RECUPLEX began processing solid and organic liquid wastes in 1953. The RECUPLEX operation experienced problems with accumulating materials in the system, resulting in elevated direct radiation levels. On April 7, 1962, a criticality accident occurred in the RECUPLEX Facility that resulted in the facility being shut down until 1964. When operations resumed from 1964 until 1976, an improved version of RECUPLEX operated; this improved version was known as the Plutonium Reclamation Facility. Combustible and acid-leached wastes were processed in the 232-Z Incinerator from 1962 until 1973. The Waste Treatment Facility recovered plutonium from aqueous liquid wastes from 1964 until 1973.

Plutonium Finishing Facilities were plagued with recurring mechanical problems and process difficulties. Radiation-related concerns included direct neutron and gamma exposures, airborne activity, and surface contamination control. As a result of these problems, respirators and periodic operation shutdowns were necessary (DOE, 2002, Chapter 2, Section 5).

5.2.5 Research and Development

Early research and development (R&D) was connected directly or indirectly with plutonium production. Simultaneously, due to the lack of knowledge regarding nuclear material reactions and their effects on biological and ecological systems, R&D in a wide variety of other topical areas was also initiated. R&D topics included radiation detection, human radiation experiments, meteorology and atmospherics, applied fish studies, radioactive field and reactor effluent studies, environmental and biological monitoring, radiobiology, and inhalation studies. As the focus of R&D has changed over time, the Hanford Laboratories have shifted from specialized research in support of nuclear weapons production to generalized research related to numerous national missions. In response to increasing national awareness of environmental issues, reactor safety and potential radiation effects have been significant areas of R&D since the early 1970s. As radiological facilities are decommissioned, R&D has also shifted to development and evaluation of cleanup methods, including technologies for managing radioactive wastes.

Initially, R&D was managed by the major site operating contractors E. I. DuPont de Nemours and Company and General Electric Company. However, since 1965, Battelle Memorial Institute has been responsible for Hanford R&D through its Pacific Northwest National Laboratory.
Although R&D involved all areas of the Hanford site, it was primarily associated with facilities in the 300 Area. Numerous buildings and facilities were involved in R&D; some of the more prominent ones are described in Section 5.2.7.

5.2.6 Tank Farms and Waste Management

Early waste management was based on a limited technical understanding of nuclear physics and engineering; it was anticipated that problems in waste management would be addressed as technology developed. Many initial waste management practices were developed by trial and error; waste

management modifications were made as knowledge increased and undesirable and impractical practices were identified. The most hazardous and largest amounts of wastes were generated by the separations operations in the 200 Areas. The Hanford site generated 58% of the total national DOE weapons waste volume. The following categories of radioactive waste were generated by Hanford operations:

- Low-level liquid wastes were generally discharged to ponds, trenches, cribs, and injection wells. There were numerous such facilities located throughout the Hanford site in which the liquids would percolate into the surrounding soil.

- High-level liquid wastes were collected in large storage tanks, from 6-11 feet below ground. These storage tanks were all located in the 200 Areas. Tanks consisted of single-shell and double-shell design. There were 149 single-shell tanks, ranging in capacity from 55,000 to 1,000,000 gallons, and 28 double-shell tanks, with capacities ranging from 1,000,000 to 1,100,000 gallons.

- Solid wastes were buried in facilities ranging from shallow pits to large lined excavations. Most burials were at least 18 feet deep. There were multiple solid waste burial sites in the 100, 200, and 300/600 Areas. Burial distance above groundwater varied from approximately 5 feet in the 100, 300, and 600 Areas to 55 feet in the 200 Areas.

- Airborne effluents were discharged into the atmosphere through stacks. During initial production efforts, air discharges were not treated or filtered. Filtration and other air cleaning equipment were added as technology developed, production increased, and impacts on the environment became better understood.

Each major functional area included its own waste management facilities and methods. Functional areas generated significantly different waste volumes and activities:

- Fuel fabrication wastes included low-level liquids, solids, and air effluents. These wastes contained predominantly uranium. Radiation from uranium associated with fuel fabrication was considered relatively minor compared to other site radionuclides and activities. However, some wastes from the 300 Area R&D activities contained much higher levels of fission products such as cesium-137 and strontium-90, activated metal components, and transuranics. Liquid low-level wastes were collected in a process sewer which emptied into ponds located east of the 300 Area. Sludge from the ponds was periodically dredged to recover the uranium. In 1973, the Waste Acid Treatment System was placed into service to collect, neutralize, and store liquid wastes from fuel fabrication and other 300 Area operations (e.g., R&D). Operations in the 300 Area did not generate high-level liquid waste. Radioactive solid waste from fuel fabrication activities was disposed of in 28 burial grounds in the 300 Area and 600 Area. Solid wastes from R&D activities were also buried in these disposal sites; radiation levels as high as 5 Roentgens per hour (R/h) were associated with such wastes. After 1973, low-level radioactive solid waste from the 300 Area was transported to 200 Area for disposal. There were no early efforts to confine particle and gas emissions; however, filters and other effluent cleaning devices were added later.

- Reactor wastes contained fission and activation products, transuranics, and uranium. Cooling water from the single-pass systems was discharged into the Columbia River. Low-level liquid wastes, including liquids from the 100-F Animal Farm experiments, were placed into trenches or

cribs from which they entered soil columns. In 1960, a peak of approximately 2 million curies of activity was released in liquid wastes. Although the radionuclides primarily consisted of short half-lives, these wastes included some with longer half-lives, such as strontium-90, cesium-137, hydrogen-3, neptunium-237, plutonium-239, and uranium. There were no high-level liquid wastes from 100 Area operations. Solid wastes consisted primarily of protective clothing, reactor hardware and components, tools, and miscellaneous trash.

- Separations and plutonium finishing wastes in the 200 Areas contained fission products (primarily cesium-137 and strontium-90) and uranium. Low-level liquids were released into the soil through ponds, trenches, French drains, cribs, and injection wells. High-level wastes were piped into underground storage tanks. Separations operations produced large quantities of liquid waste containing high levels of radioactive materials along with hazardous chemical constituents. In Evaporator buildings, water from underground tanks was boiled off, thus concentrating the radioactive content in slurry that was returned to the tanks. Solid wastes that were disposed of in 200 Area burial grounds consisted primarily of process hardware, construction debris, protective clothing, and soil contaminated by spills from storage tanks. Since 1988, transuranic waste has been stored aboveground in the Central Waste Facility. Since the beginning of operations, airborne effluents were released through 200 foot-high stacks. During early production years, no treatment was provided to control airborne releases. The predominant radionuclide released in early operations was iodine-131; other contaminants included ruthenium-103, ruthenium-106, cerium-144, and strontium-90. After 1947, sand filters, fiberglass filters, and silver reactor filters were provided to reduce airborne emissions from the separations operations.

There were no known radioactive waste disposals in the 400 Area. In addition to radioactive wastes resulting from on-site operations, the Hanford site also accepted low-level solid wastes from 58 other off-site generators. Included in this off-site waste were 50 Navy submarine reactor compartments, which were buried in the 200 East Area.

Numerous problems associated with waste management operations (waste fires, ruptured containers, storage tank leaks, and crib overflows) resulted in the spread of contamination and elevated radiation levels. Exposure rates up to 200 R/h were encountered during routine handling of solid waste. Waste fires occurred in solid waste burial sites in all major areas. From one such fire in the 618-4 burial ground, particles were released that traveled as far as far 1,500 feet from the burial site with contact radiation levels of up to 4.5 R/h. Containers of waste were ruptured during transport due to the weight of backfill soil. One of these incidents in the 200 Area resulted in contamination of 4 square miles of surface soil. Similar releases occurred in the 300 Area. In 1957, a burial container containing REDOX hardware was dropped during transit to a 200 Area burial site, resulting in ground contamination of 2 R/h. There were frequent leaks in underground storage tanks and waste transport lines. Sixty-seven of the 149 single-shell tanks have experienced known or suspected leakage (no leakage from double-shell tanks has been reported). The estimated release from these leaks is approximately 1 million curies—mostly cesium-137. A transfer line from T Plant leaked in 1955, resulting in soil contamination levels of 100 rad/h; another T Plant leak in 1973 released 115,000 gallons from a waste tank to surrounding soil. A 1953 chemical reaction in an underground vault at the U Tank Farm caused localized contamination. Many cribs overflowed or otherwise malfunctioned. Examples include the 216-U-1, -2, and -16 cribs, which released uranium-containing liquids to surrounding soil and groundwater. Crib overflows have also resulted in vegetation and wildlife contamination. In 1945, the dike of the 300 Area pond broke and released 14 million gallons

of low-level liquid waste into the Columbia River. Each of the eight reactor retention basins has leaked, allowing low-level liquid waste to enter underlying soil. Prior to installation of filters in 1947, flakes contaminated with iodine-131, ruthenium-103, ruthenium-106, cerium-141, strontium-90, and other radionuclides were occasionally discharged from the separations stack and contaminated the areas around the Separations Plants. Personnel in the vicinity of the plants were required to wear respiratory protection. An intentional release of over 8000 curies of iodine-131 from T Plant was performed in 1951. This experimental release, called the "Green Run," was conducted to study the mechanisms of contamination spread.

5.2.7 Summary of Key Hanford Facilities

Table 5-2 summarizes the key Hanford site radiological facilities operations.

Table 5-2: Key Hanford Site Facilities and Operations (September 1946 through December 1990)

Table 5-2 and corresponding notes span three pages

Areas	Key Facilities	Period of Operation	Description
100	B Reactor	1944 -1946; 1948-1968	Each production reactor complex included the 105 Building, which contained the graphite core reactor for irradiation of uranium fuel elements to produce plutonium, storage pool, and handling facilities for irradiated fuel; the 103 Building for storage of unirradiated fuel elements; and the 107 retention basins for reactor cooling water
	D Reactor	1944 -1967	
	F Reactor	1945 - 1965	
	H Reactor	1949 - 1965	
	DR Reactor	1950 - 1964	
	C Reactor	1952 - 1969	
	KW Reactor	1955 - 1970	
	KE Reactor	1955 - 1971	
	N Reactor	1963 - 1987	Similar complex to production reactors, with the exception of the facility for utilizing heated water to operate power-producing turbines
	100-Animal Farm	1949 - Unknown	Area for conducting research on effects of radiation and radioactive materials on animals and fish
	108-F	1949 - 1977	Biology Laboratory
	108-B	1949 - 1955	Tritium Extraction Facility
200	T Plant	1944 - 1956; 1958 - 1990s	T Plant was in 200 West; B Plant in 200 East; used tri-butyl phosphate batch process on irradiated fuel elements to separate plutonium from uranium and fission products; each plant included 221 Chemical separation buildings, 224 bulk reduction to further purify and concentrate plutonium, 222 sample preparation laboratories, 291 exhaust buildings, and 242 evaporator; T and B Plants were modified to perform decontamination (T Plant) and Fission Product Recovery (B Plant) in the later time period
	B Plant	1945 - 1956; 1968 - 1985	
	U Plant	1952 - 1958	Design similar to T and B Plants but never used for separations; used instead for testing and maintenance of T and B components and processes
	C Plant	1952 – 1956; 1962 - 1967	Pilot Plant for REDOX and PUREX operations
	S Plant (REDOX)	1952 - 1967	Continuous flow solvent extraction process using hexone
	A Plant (PUREX)	1956 - 1972; 1983 - 1988	Continuous flow solvent extraction process using tri-butyl phosphate
	U Trioxide Plant	1956 - 1972	Conversion of separated uranium to UO_3
	231-Z	1945 - 1956	Finishing building located in 200 West; converted material from Bulk Reduction Facilities to

Table 5-2: Key Hanford Site Facilities and Operations (September 1946 through December 1990)

Table 5-2 and corresponding notes span three pages

Areas	Key Facilities	Period of Operation	Description
			plutonium nitrate paste
	234-Z5	1949 – 1976; 1978	Plutonium finishing
	242-Z	1965 - 1976	Americium recovery
	212-N, 212-P, and 212-R	1944 - 1976	Lag storage buildings located in 200 North for storage of irradiated fuel awaiting dissolution
	213-J and 213-K	1944 - 1993	Magazine storage buildings located in 200 North for storage of plutonium nitrate paste from 231-Z
	241-B, 241-C, 241-T, and 241-U	Constructed from 1944 – 1988	Underground storage tanks for high-level liquid waste from separations operations; each group contained 16 tanks; B and C tank farms were in 200 East; T and U farms in 200 West
	236-Z	1964 – 1979; 1984 – 1985	Reclamation of plutonium from waste
	232-Z	1961 - 1973	Incinerator and leach for plutonium recovery
300	303-A, B, C, D, E, F, G, J, K, and M	Built 1944 1988; still in use	Used for storage of uranium metal to be fabricated into fuel elements
	305	1943 – 1977	Test reactor for development of fuel and reactor materials
	313	1944 – 1971	Metal Fabrication Building; uranium slugs were prepared and canned for irradiation
	314	1944 - 1971	Press Building; extrusion and straightening of uranium rods in preparation for cutting into slug lengths and canning
	3706	1945 – (Used as office space into the 1990s)	Radiochemistry Laboratory to support all Hanford Site operations
	321	1944 - 1988	Separation Building, also known as cold semi-works; pilot studies to support development of separations processes
	326	1953 - Present	Physics and Metallurgy Laboratory
	306	1957 - 1984	Fuel Element Pilot Plant
	333	1961 - 1988	Fuel Clad Building for N Reactor
	327	1953 - 1987	Post-Irradiation Test Facility
	325	1953 - Present	Radiochemistry Laboratory/Cerium Recovery
	308	1960 - 1990	Plutonium Fuels Pilot Plant
	309	1960 - 1969	Plutonium Recycle Test Reactor
	324	1966 – Currently undergoing decommissioning	Waste Technology Engineering Laboratory
	328	1953 - Present	Mechanical Development
	329	1952 - Present	Biophysics Laboratory
	320	1966 - Present	Low-Level Radiochemistry Building
	318	1967 - 1971	High-Temperature Lattice Test Reactor
	335	1968 - 1984	Sodium Test Facilities
	336	1969 - 1984	
	337	1970 - 1984	Technical Management Facility; later housed the Biology Laboratory from 108-F
400	Fast Flux Test Facility (FFTF)	1980 - 1994	Sodium-cooled reactor for testing of materials
	427	1983 - 1994	FFTF fuels and materials examination

This table was created from information obtained from ORAUT-TKBS-0006-2, ORAUT-TKBS-0006-4, ORAUT-TKBS-0006-5, and DOE, 2002.

5.3 Radiological Exposure Sources from Hanford Operations

During the period of September 1946 through December 1990, there was a potential for radiation exposures from a variety of internal and external sources. The primary mission of the Hanford site was production of plutonium; consequently, there were potential exposures to that material. In addition, other operations necessarily related to plutonium production involved potential exposures. For example, fuel fabrication from natural uranium gave rise to potentially direct beta and photon exposures and to airborne exposure. Reactors used to irradiate fuel elements generated direct beta, photon, and neutron radiation fields, as well as the potential for surface and airborne contamination by uranium and a wide variety of fission and activation products. Separations processes, research and development activities, and the collection and disposal of radioactive wastes also resulted in potential direct exposures to direct alpha, beta, photon, and neutron radiation fields, as well as to surface and airborne contamination by uranium and a wide variety of fission and activation products.

5.3.1 Alpha Particle Emissions

Primary alpha particle-emitting radioactive materials at the Hanford Site include uranium, plutonium, and other transuranic materials produced by the irradiation of uranium fuel. Table 5-3 lists the alpha-emitting radionuclides and their primary alpha energies.

Table 5-3: Hanford Site Alpha-Emitting Radionuclides

Radionuclide	Energy (MeV)
Plutonium-238	5.46 (28%), 5.50 (72%)
Plutonium-239	5.11 (11%), 5.16 (88%)
Plutonium-240	5.12 (24%), 5.17 (76%)
Americium-241	5.44 (13%), 5.49 (85%)
Neptunium-237	4.78 (75%), 4.65 (12%)
Uranium-234	4.72 (28%), 4.77 (72%)
Uranium-235	4.37 (18%), 4.40 (57%), 4.58 (8%)
Uranium-238	4.15 (25%), 4.20 (75%)

5.3.2 Beta Radiation Fields

The primary sources of beta exposure were fission and activation products from reactor operations. The greatest potential for exposure to beta radiation from these materials was during the separations process and subsequent waste handling after the material was separated from the solid fuel and placed in a dispersible form. Beta radiation was also emitted by unirradiated uranium fuel, but at significantly lower levels than encountered after the fuel was irradiated during reactor operations. Table 5-4 lists major beta-emitting radionuclides and the maximum beta energies and abundance of their primary beta energies.

Table 5-4: Hanford Site Beta-Emitting Radionuclides	
Radionuclide	**Energy (MeV)**
Strontium-90/Yttrium-90	0.546 (100%)/2.28 (100%)
Cesium-137	0.512 (95%)
Iodine-131	0.248 (2.1%), 0.334 (2.2%), 0.607 (90%)
Cerium-144	0.318 (77%), 0.185 (20%)
Ruthenium-106/Rhodium-106	3.54 (79%), 2.41 (10%), 3.03 (8%)
Ruthenium-103/Rhodium-103	0.226 (91%)
Protactinium-234m (uranium decay chain)	2.29 (98%)
Thorium-234 (uranium decay chain)	0.103 (21%), 0.193 (79%)
Plutonium-241	0.021 (100%)

5.3.3 Neutron Exposures

Areas at Hanford where there is a potential for neutron exposure include (ORAUT-TKBS-0006-6):

100 Area
- 105-B, 105-C, 105-D, 105-DR, 105-F, 105-H, 105-KE, 105-KW, 105-N reactors

200 Area
- 221-U Facility cinder block building attachment (known as 271-U)
- 224-T Facility to concentrate plutonium solutions and store sources
- 231-Z Plutonium Isolation Facility
- 232-Z Incinerator and Leach Facility
- 234-5Z Primary Plutonium Handling Facility
- 236-Z Recuplex/Plutonium Reclamation Facility
- 242-Z Americium Recovery Facility
- 2736-Z Plutonium vaults

300 Area
- 305-B Test Reactor
- 308 Plutonium Fuels Pilot Plant (PFPP)
- 309 Plutonium Recycle Test Reactor (PRTR)
- 318 Radiological Calibrations Facility
- 324 Chemical and Materials Engineering Laboratory
- 3745A Calibrations Laboratory
- 3745B Accelerator Facility

400 Area
- Fast Flux Test Facility (FFTF)

The circumstances of neutron exposure at these facilities are different based on the primary method of neutron radiation generation. At the 200 and 300 Area Plutonium facilities, neutron radiation is generated from plutonium either by spontaneous fission or, importantly, by alpha particle interaction

with light elements such as oxygen, fluorine, and beryllium. These interactions are commonly referred to as alpha-n reactions. At the Hanford 100 and 400 Area Nuclear Reactor facilities, neutrons are generated by fission of uranium and plutonium in the reactor core. These two methods of neutron generation comprise the majority of Hanford worker neutron exposures. There is little potential for significant unrecorded neutron dose in the 300 Area Radiological Calibration (318, 3745B) and Accelerator (3745A) facilities because these are the facilities used to develop, test, and calibrate Hanford dosimetry and instrumentation systems (ORAUT-TKBS-00006-6).

5.3.4 Photon Exposures

Photons associated with plutonium are of low energy and would be shielded by construction materials in Processing and Handling Facilities. However, the fission process releases high levels of photon radiation, and many of the fission and activation products resulting from fuel irradiation in reactors decay by photon emission. Biological shields around reactor cores reduced the levels of fission photons and photons from irradiated fuel within the core. After their discharge from the reactor, irradiated fuel elements were stored underwater and handled with remote tools to limit exposures. Photons from irradiated fuel were a concern throughout the stages of the plutonium production process, including transportation, chemical separation, waste management, and equipment maintenance. Research and development activities used a wide variety of radionuclides with photon emissions similar to those generated in the fuel irradiation operations. ORAUT-TKBS-0006-6 provides information regarding photon sources and energy spectra associated with various site operations.

5.3.5 Incidents and Fires

NIOSH reviewed documents that contain general and specific references to problems related to radiation exposure control, including many of the Radiation Protection Organization's routine reports. There were numerous incidents related to the Hanford Waste Management Facilities and processes. Waste fires occurred at solid waste burial sites in all major areas. Containers of waste were ruptured as a result of both transport and the weight of backfill soil. There were frequent leaks in underground storage tanks and waste transport lines. Sixty-seven of the 149 single-shell tanks have experienced known or suspected leakage (no leakage from double-shell tanks has been reported). The estimated total release from these leaks is approximately 1 million curies—mostly cesium-137. Cribs overflowed or otherwise malfunctioned. Crib overflows have also contaminated vegetation and wildlife. Liquid waste retention basins/ponds have leaked. Some specific examples are as follows:

- In 1948, the dike for the process liquid waste pond in the 300 Area broke, releasing the pond contents into the Columbia River.
- A 1953 chemical reaction in an underground vault at the U Tank Farm caused localized contamination.

- Fires occurred in the 618-2 and 618-4 waste burial grounds in 1954. Contamination from the 618-4 fire was dispersed as far as 1500 feet from the burial site and radiation levels on contact with contaminated particles reached 4.5 R/h.

- A transfer line from T Plant leaked in 1955, resulting in soil contamination levels of 100 rad/h.

- In 1957, a burial container containing REDOX hardware was dropped during transit to a 200 Area burial site, resulting in ground contamination to a level of 2 R/h.

- Rupture of a waste container during burial in the 200 Area contaminated of 4 square miles of surface soil.

- The 216-U-1, -2, and -16 cribs malfunctioned, releasing uranium-containing liquids into the surrounding soil and groundwater. Plutonium reached the water table in the 216-Z3 crib.

- Plutonium accumulated in the soil at the 216-Z9 crib to the extent that remediation was necessary for criticality safety reasons.

Several significant incidents within operations facilities were reported. Specific examples follow.

- Throughout 1949, repeated high air concentrations occurred in the Building 234-5Z (Plutonium Finishing) process rooms and laboratories. Use of respiratory protection was required for workers in the affected facilities.

- A fire involving plutonium turnings occurred in the RMA line of Building 234-5Z in 1954, contaminating the rear section of the line.

- In 1962, there was a nuclear criticality involving plutonium solutions in the scrap recovery room of the RECUPLEX Facility. No significant worker exposures occurred, but the room was contaminated.

- An explosion of an ion exchange column, containing approximately 100 grams of americium-241, occurred in a glove box in Building 242-Z in 1976. The operator was highly contaminated and experienced facial cuts, burns, eye injuries, and internal americium-241 deposition.

NIOSH-reviewed documents contain sparse mention of fires occurring during the fuel fabrication operations. However, based on the history of other fuel fabrication operations, which entailed extrusion and machining of uranium metal, it is likely that such fires frequently occurred. Prior to installation of filters in 1947, flakes contaminated with iodine-131, ruthenium-103, ruthenium-106, cesium-141, strontium-90, and other radionuclides were occasionally discharged from the separations stacks and contaminated the areas around the Separations Plants. Personnel in the vicinity of the plants were required to wear respiratory protection. In 1954, ruthenium tetraoxide flakes were released from the stack of the REDOX Separations Facility, causing widespread land area contamination and requiring cleanup efforts.

In 1951, over 8,000 curies of iodine-131 were intentionally released from T Plant. This experimental release, called the “Green Run,” was conducted to study the mechanisms of contamination spread. Additional iodine-131 releases occurred in 1951 as a result of failures of filtration systems in the B and T Plants during experiments in reducing cooling time for irradiated fuel.

6.0 Summary of Available Monitoring Data for the Proposed Class

Radiation protection was a major concern at Hanford from the beginning of operations. Throughout most of Hanford's history, considerable research was conducted to improve survey instruments, effluent clean-up mechanisms, monitoring instrumentation, workplace air-sampling practices, and understanding of the biokinetics of radionuclide intakes (ORAUT-OTIB-0002). The science and practice of monitoring for exposures from plutonium, uranium, and mixed fission and activation products were in their infancy in the 1940s. However, monitoring knowledge and assay skills were rapidly being developed and improved; thus, the scope of worker monitoring expanded over time.

The primary sources of monitoring data for this evaluation include the NIOSH Site Research Database (SRDB), the NIOSH OCAS Claims Tracking System (NOCTS), the Comprehensive Epidemiologic Data Resource (CEDR) Database, the DOE Hanford Radiological Exposure (REX) System Database, and the DOE Hanford Declassified Document Retrieval System. In addition to the REX database (maintained by the Hanford Site) and the CEDR database, NIOSH investigated various Hanford declassified databases (with DOE Hanford assistance) for available internal and external monitoring data. Furthermore, the NOCTS database was reviewed for claimant exposure data. Copies of many of the Hanford records are contained in the SRDB. NIOSH reviewed these sources and identified personal monitoring data (e.g., film badge exposure results, thermoluminescent dosimeter (TLD) monitoring results, and bioassay results) and area monitoring data.

6.1 Hanford Internal Monitoring Data

Summaries of the available *in vitro* and *in vivo* data, as well as overviews of sampling and analytical protocols, are provided in the following subsections. Additional details, including analytical methods, detectable activities, and reporting protocols can be found in *Hanford Site—Occupational Internal Dose* (ORAUT-TKBS-0006-5).

The major sources of intakes during the 1946 through 1990 timeframe have been plutonium, americium-241 (either as an ingrown contaminant in the plutonium or as a separated waste product), uranium, fission products, activation products, and tritium (ORAUT-TKBS-0006-5, page 11). One of the priority tasks for a special studies group formed in 1944 was to determine a way to measure plutonium in the body. Limits on the amount of plutonium in the body were set as early as 1944; after experimentation with various methods, routine urine sampling and analysis for plutonium were initiated in 1946. Urinalysis for uranium appears also to have begun in 1946 and was well-established by 1948. Urinalysis for fission products began in this timeframe as well, although the Wilson document indicates that separation from potassium-40 was not always successful prior to 1949 (Wilson, 1987). Since 1949, there has been monitoring for numerous radionuclides at Hanford because of the complex scope of work conducted over the succeeding years. This work included many research projects and special campaigns. Correspondingly, numerous monitoring and analytical techniques have been utilized and improved over time (ORAUT-TKBS-0006-5).

Hanford records list a wide spectrum of radionuclides that were monitored, and an even longer list of codes used to identify the radionuclides, groups of radionuclides, specific measurement techniques, or combinations of radionuclides and techniques. Many of these radionuclides were of concern only to a small set of workers on a single research project, or to workers (for instance, radiation monitoring

technicians) whose tasks potentially exposed them to many different sources of radionuclides (ORAUT-TKBS-0006-5, page 11).

6.1.1 *In Vitro* Data Availability

The practice of having workers collect bioassay samples while at home began very early in the Hanford program (1946) and has continued throughout the history of Hanford (Wilson, 1987). Home sampling was used to prevent contamination of samples in the workplace. The sampling protocol used most frequently was a simulated 24-hour sample obtained by sampling from evening through morning on two consecutive nights (or the temporal equivalent for shift workers). Termination samples were often simulated 12-hour samples (ORAUT-TKBS-0006-5, page 14).

In vitro analyses were performed in-house until 1965. At that time, the DOE Richland Office established a contract for *in vitro* analyses with the United States Testing Company (UST), which built a commercial low-level radiochemistry laboratory in north Richland and operated it until 1990 (ORAUT-TKBS-0006-5, page 14).

The REX system serves as the primary repository for Hanford *in vitro* data. A summary of the *in vitro* records stored in the REX database is presented in Attachment 1. It should be noted that the record totals presented in the table are based only on data that is currently in a format (electronic data tables) conducive to large scale data queries. Though much of the data collected prior to the routine use of computerized database storage systems (approximately 1958) has now been uploaded into REX database tables, some of this earlier data still remains stored predominantly in its original format such as individual paper copies and/or electronic images of those paper copies. As such, counts of analytical records presented in Attachment 1 in some cases do not represent all records that are available. An example of this discrepancy would be a lack of fission products results shown prior to 1958 in the summary table, whereas various reports and individual monitoring history files contain fission product *in vitro* analytical results as early as 1948.

6.1.1.1 Plutonium

Plutonium represented a primary intake source at Hanford. With the exception of a few standards in radiochemistry laboratories, and a plutonium-238 purification experiment in the 325 Building C-cell around 1967, plutonium at Hanford was comprised of a mix of radionuclides, namely plutonium-238, plutonium-239, plutonium-240, and plutonium-241. The activity of plutonium-242 in plutonium mixtures at Hanford was too small to contribute significantly to dose (ORAUT-TKBS-0006-5, page 17). Routine urinalyses for plutonium started in September 1946 (Wilson, 1987). The first plutonium bioassay analysis consisted of lanthanum fluoride precipitation and thenoyl trifluoroacetone extraction and gross alpha counting. Electrodeposition on a stainless-steel disk combined with nuclear track emulsion (autoradiography) started in December 1952 (ORAUT-TKBS-0006-5, page 15).

Prior to October 1983, the recorded value was the total alpha activity from plutonium, which would have included activity from plutonium-238, plutonium-239, and plutonium-240. The recorded results would not have accounted for any plutonium-241 or americium-241 present in the urine. The results might have been reported as either plutonium or plutonium-239; however, until October 1983, the result was really the total alpha activity from isotopes of plutonium. Results on plutonium urinalysis

sheets were recorded in units of dpm/sample, but the same results were recorded in units of µCi/sample in an electronic database (ORAUT-TKBS-0006-5, page 15).

In October 1983, several changes were made. The lanthanum fluoride/ thenoyl trifluoracetone method was replaced by the use of anion exchange columns, alpha spectrometry analysis replaced autoradiography, and chemical yield was established for each sample separately by use of a plutonium-242 tracer. The results of plutonium-238 and plutonium-239 + plutonium-240 have been reported separately since then (ORAUT-TKBS-0006-5, page 16).

Fecal sampling was normally done in response to suspected intakes; however, routine fecal sampling was used for some high-risk plutonium workers, mostly operators at PUREX and the Plutonium Finishing Plant, from 1986 through June 1989 (ORAUT-TKBS-0006-5, page 17). Fecal samples were usually not analyzed in total (i.e., were aliquoted after muffling, dry ashing, and wet ashing); hence, more than one analysis result for a given sample was possible and will often be found in the REX database (ORAUT-TKBS-0006-5, page 16).

6.1.1.2 Americium

Americium was usually a trace contaminant in plutonium mixtures. However, americium was separated from plutonium at the Isolation Building (231-Z) in the early years of operation (Gerber, 2005). There was also an americium recovery operation located in 242-Z of the Plutonium Finishing Plant that operated from 1965 until 1976 (Gerber, 2005). Therefore, waste tanks, transfer lines, and parts of the Plutonium Finishing Plant contained americium-241 that was chemically separate from plutonium (ORAUT-TKBS-0006-5).

Based on a review of the historical documents and bioassay records prior to 1964, NIOSH has found no evidence of an Americium Bioassay program at Hanford. The first americium records in the REX database show 41 urinalyses for americium-241 in 1964, collected from 19 workers. There are no records of americium bioassay in 1965 or 1966; there are 168 results in 1967. The 1967 results are a combination of urine and fecal results. The 1967 results are all from special samples from six workers who were involved in the same potential intake accident on May 2, 1967. From 1968 on, there are americium bioassay results in the REX database (ORAUT-TKBS-0006-5).

6.1.1.3 Curium

The curium isotopes of concern were curium-242 and curium-244. Most sources of curium at Hanford were minor calibration sources or minor constituents in an actinide mixture. However, extraction of curium-244 from high-level waste occurred at the 325 Building sometime in the 1970s. Since the curium and americium procedures were the same, the results would have been reported as curium only if so requested through the bioassay request system (this was prior to the use of alpha spectrometry). After 1985, the chemistry is the same as americium, but americium-241, curium-242, and curium-244 were reported separately if requested (Battelle Northwest, 1985).

6.1.1.4 Tritium

The earliest report found to date on tritium urinalysis at Hanford was written in 1949 by Jack Healy, a lead internal dosimetrist at Hanford for many years (Healy, 1949). Tritium urinalysis performed from March 1950 through March 1951 is also referenced in the April 4, 1951 meeting minutes of the P-10 Hazards Control Committee (Kornberg, April 1951).

The first urinalyses were performed by measuring the ionization current in acetylene (produced from water containing tritium) by using a vibrating reed electrometer. This procedure was thought adequate by Hanford, but apparently was too time-consuming to handle the increased sampling frequencies that started in 1951; daily sampling was implemented for those working in the P-10 hood rooms, and weekly sampling was implemented for others in the P-10 exclusion area (Healy, 1949; Kornberg, August 1951; Reed, 1952; Healy, 1950). A sensitivity for the acetylene tritium analysis is stated as 1.5 -2.0 μCi/L of the sample (Healy, 1950). An internal memo (Parker, 1950) that referred to the acetylene method for urinalysis also provides a sensitivity of approximately 1.2×10^{-3} μCi/cc (1.2 μCi/L) in water (Parker, 1950).

A program was started to develop new techniques for routine analysis. One such method placed the liquid sample in an aluminum carbide generator with the evolved methane being counted in a proportional counter. This procedure showed promise, but there were problems obtaining the reagents needed to perform the analysis, namely aluminum carbide. Healy, in describing the development of the new method states that "it was hoped this method would have a sensitivity slightly better than the acetylene method" (Healy, 1950).

The next approach was using an internal Geiger-Mueller counter filled with hydrogen gas. This method was successful and was developed into the routine sampling analysis with a capacity of 6-8 samples per hour per instrument. Details of this method were provided in a Healy letter that appears to indicate a process sensitivity of 20 counts per minute of tritium per microcurie of tritium per liter of urine (20 c/m/μCi/L) (Kornberg, August 1951; Healy, 1951).

Liquid scintillation counting was implemented for tritium bioassay at the Savannah River Site in 1958 and it is reasonable to assume that Hanford did so at about the same time (ORAUT-TKBS-0006-5, page 22-23). In an interview with Matt M. Lardy, Mr. Lardy stated that liquid scintillation counting of a 1-ml aliquot of raw urine has been used since UST was awarded the bioassay contract in 1965 (Personal Communication, 2003).

Tritium bioassay results were not recorded in the REX database until 1984. However, tritium doses were included in external dose reports from 1949 through 1987; thus, "monitored" workers would be determined by tritium dose listed in external dose records. A zero dose is indicative of a monitored worker; however, there are only two of these in the database. Having no value listed under "tritium" might indicate either an unmonitored worker or a monitored worker with less-than-recordable dose. No tritium doses are listed on external dose reports for the periods 1955 through 1960, 1970, 1971, and 1973 through 1984. This means that either there was no bioassay monitoring during these periods or the intakes were below some reporting criteria (ORAUT-TKBS-0006-5, page 52).

6.1.1.5 Uranium

Uranium exposure at Hanford involved principally three physical forms: depleted, natural, and slightly enriched uranium. Uranium-233 was also isolated from irradiated thorium at PUREX from 1966 to approximately 1971. Small numbers of researchers may have experimented with more enriched uranium at different times (e.g., metallurgy on commercial-grade fuel), but such exposure would have been limited to small groups over short periods of time (ORAUT-TKBS-0006-5, page 24).

Because chemical toxicity was the principal concern for uranium exposures at the UO_3 Plant, one sampling method required obtaining both a Friday evening sample and Monday morning sample. The date this sampling method began is not known; however, it may have been in the 1970s or possibly earlier. This procedure was changed to Monday-morning-only sampling in the early 1980s (ORAUT-TKBS-0006-5, page 26).

According to Wilson (1987), the uranium urinalysis program prior to 1948 was not reliable. The fluorometric method, which fused uranium from raw urine with sodium fluoride and measured the fluorescence when the compound was exposed to ultraviolet light, was implemented sometime during the first half of 1948 (Wilson, 1987; Healy, 1948). This method was used for elemental uranium analyses, with refinements over the years including some upfront chemistry on the raw urine, until about 1991, when it was replaced by kinetic phosphorescence analysis (Personal Communication, 2003).

When alpha spectrometry was introduced in 1983, two uranium urinalyses procedures were offered: the elemental procedure and the alpha spectrometric procedure. The elemental procedure was typically used for workers exposed to natural or slightly enriched forms of uranium; the isotopic procedure (alpha spectrometric) was used for depleted or more-than-slightly enriched forms of uranium. In general, personnel working in the production facilities were monitored by the elemental analysis, whereas Pacific Northwest Laboratory workers, because of the wide scope of research projects that occurred over the years, were monitored by the isotopic analysis (ORAUT-TKBS-0006-5, page 27). The Hanford Bioassay database shows that a few urinalyses were obtained for uranium-233, mostly in 1970. No information has been found regarding how the analyses were performed or the units of the recorded results. Copies of an earlier database show the units to be μg/L, consistent with the units for all uranium analyses at that time; however, the recorded values are much too small to realistically be in μg/L, with the exception of a single value in 1969. The recorded values appear to be similar to plutonium alpha measurements at that time; it is probable, but not verified that autoradiography was used for these bioassays because of the high specific activity of the uranium-233 and the major contaminant uranium-232. Fecal samples were rarely obtained for potential uranium intakes (ORAUT-TKBS-0006-5, page 29).

6.1.1.6 Fission Product Analysis

Fission product urinalysis was the method used to monitor for intakes of fission products until the implementation of whole-body counting in 1960. Routine fission product urinalyses started in January 1947, but the results from the method used (ferrous hydroxide precipitation of the supernatant from the plutonium lanthanum fluoride procedure) were considered erratic until 1948. Therefore, data prior to 1948 should be considered unreliable and should be ignored. The procedure initiated in 1948 was to add a strontium carrier to the aluminum oxide solution for the plutonium procedure, then

precipitate lanthanum hydroxide. This procedure was shown to extract the rare earths and strontium with yields ranging from 90% for cerium to 23% for strontium. The dried planchet was counted for beta activity with an approximate detection level of 30 dpm (Wilson, 1987; Healy, 1948). This same procedure was modified in 1954 with the addition of a cerium carrier. This procedure was also listed in the compilation of procedures referred to as the "Old Bioassay Bible," but that same compilation had a separate procedure for detecting strontium-90 in urine. A memo in the Old Bioassay Bible discusses the initial use in November 1958 of a gas-flow, beta proportional counter, which resulted in increased counting efficiency. The new detection limit was stated as 1.4 × 10-5 μCi/sample, based on the counting efficiency of strontium-90. Gross fission products are also mentioned by Lardy in his 1970 correspondence regarding detection limits for selected radionuclides. This correspondence includes a brief description that implies the same procedure was still available, although probably rarely used (ORAUT-TKBS-0006-5, page 29-30).

6.1.1.7 Strontium

The REX database records show the use of fission product urinalyses to obtain strontium-90 exposure data prior to 1965. Records of strontium-90 urinalyses, both routines and specials, begin to appear in the database in 1965. Beginning in 1982, actual analytical results were recorded in the database; that is, results were not truncated at a reporting level (ORAUT-TKBS-0006-5, page 30).

6.1.1.8 Promethium

Hanford manufactured promethium-147 heat sources. The high-activity work (kilocuries) took place in the 325 Building, but some exposure apparently occurred as early as 1962 or 1963 in the 222-S Chemistry Laboratory and the 325 Building, and occurred as late as 1971 in the 308 Fuels Laboratory (Glover, 1964; Howell, 1969). The REX database shows only seven promethium-147 urinalyses from 1972 to 1975, but an increased number of analyses from 1976 to 1979; this suggests that the project may have experiences a brief hiatus around 1976 and continued for a few years thereafter. In addition, animal studies were conducted with promethium-147 as part of research to develop a human biokinetic model for the behavior of promethium in the body, so animal tenders might have been exposed to low levels of promethium-147. A small human volunteer study (14 volunteers) using promethium-143 was conducted in 1967 or 1968 (Palmer, 1970) (12 volunteers: injection of 0.1 μCi each; 2 volunteers: ingestion of 10 μCi each).

In the late 1960s, fecal samples were analyzed for promethium-147 for some potential intake events. The minimum detectable activity, or at least the lowest reporting level, appears to be 1.67×10^{-5} μCi/kg. A minimum detectable activity for fecal samples does not appear in laboratory statements of work during the 1970s, but reappears in the 1980s: 28–110 dpm/sample in 1982 depending on sample size (roughly 400 dpm/kg); 220 dpm/sample from 1983 to the 1990s (ORAUT-TKBS-0006-5, page 32).

Only one description of the procedure was found; the procedure itself appeared in documents dated 1970, 1974 and 1977 (Lardy, 1970; UST, 1974). As described, promethium and rare earths were precipitated as the fluoride. Interferences such as zirconium, scandium, and IV actinides were removed by extraction by thenoyl trifluoracetone in xylene, first at a pH less than 1, then at a pH of about 4. The final sample was counted by liquid scintillation. Remaining rare earths were

distinguished from promethium-147 by proper setting of the counting window on the liquid scintillation spectrometer (ORAUT-TKBS-0006-5, page 32).

6.1.1.9 Polonium

From 1945 through the early 1950s, bismuth slugs were irradiated in Hanford reactors to produce polonium-210. The slugs containing the polonium were shipped offsite for processing at the Monsanto facility in Ohio (Tilley, 1945; DOE, 1997). Work with pure polonium-210 occurred in the 308 Building in 1968 and again in 1975. NIOSH could not determine whether the work in the 308 Building occurred continuously throughout that period or just during those two years (ORAUT-TKBS-0006-5).

A polonium urinalysis procedure, using deposition on silver foil from a hydrochloric acid solution of urine salts, was developed as early as 1948; this procedure was used in response to a contamination incident involving two workers with a polonium-beryllium neutron source. No polonium was found in the urine of the two workers (Thorburn, 1948), and these results were not found in the REX database. In the Hanford files, NIOSH discovered considerable activity, from about 1968 through the mid-1970s, toward initiating a bioassay procedure and establishing a biokinetic model for polonium-210. UST was asked to develop a bioassay procedure in March 1968 and did so shortly thereafter; thus, concern for possible intakes apparently became important in early 1968 (ORAUT-TKBS-0006-5, page 33). Polonium bioassay results appear in the REX database for the years 1968 through 1983.

6.1.1.10 Neptunium

At PUREX, from 1958 through 1972, and at REDOX from 1960 through 1967, neptunium-237 was removed from the dissolved fuel, purified, and packaged for shipment offsite (ORAUT-TKBS-0006-5, page 34; Pickard, 1968).

The REX database contains only four bioassay samples for neptunium-237 in the 1970s, all baseline samples for Pacific Northwest National Laboratory workers. No routine samples or ending work samples were collected. All four samples had the same recorded value—1 × 10-7 with no units shown. The practice at the time was to record the activity of excreta samples in units of μCi, but it has not been determined to date if the units are μCi/sample or μCi/L. No information about the analysis method has been found (ORAUT-TKBS-0006-5, page 34).

A few sample results appear in REX in the 1980s, mostly for Pacific Northwest National Laboratory employees. The units are in dpm/sample. The 1983 statement of work with UST shows a non-routine analysis for neptunium-237 with contractual detection levels of 0.02 dpm/sample for urine samples and 0.1 dpm/sample for fecal samples, which levels were consistent with alpha spectrometry for plutonium and americium at the time (Battelle Northwest, 1983).

Although mostly neptunium-237 by mass, the small mass of plutonium-238 in the product produced most of the radioactivity. Plutonium bioassay was considered sufficient to monitor for neptunium intakes (ORAUT-TKBS-0006-5, page 34).

6.1.1.11 Other Limited-Exposure Radionuclides

Hanford has always been a center for research, first as part of Hanford Works, and then as part of Pacific Northwest National Laboratory from 1965 to present. As such, small-scale (in terms of either the number of persons or activity of the source) use of various radionuclides not addressed above has occurred throughout the history of the Hanford site. The following discussion, addressing carbon-14, thorium-232, radon, yittrium-90, thorium-227, actinium-227, sulfer-35 and phosporous-32, is not comprehensive (ORAUT-TKBS-0006-5, page 34).

Carbon-14 exposure occurred at the 3731 Building in the mid-1950s when irradiated graphite samples were brought to the building from the operating reactors for destructive testing. No information has been uncovered about what bioassay, if any, was done. Carbon-14 was also used as a tracer in biological experiments (ORAUT-TKBS-0006-5, page 34).

There are some thorium urinalysis samples that date back to 1979. These samples are identified as either thorium or thorium-232. The thorium urinalysis was a total thorium analysis by spectrophotometry with a detection level of 1 μg/L. The thorium-232 analysis was specific for thorium-232 using alpha spectrometry (ORAUT-TKBS-0006-5, page 34).

There are some 1967 urinalysis results for sulfer-35. According to Lardy (1970), analysis was performed by ashing and then followed by liquid scintillation counting (Lardy, 1970).

A radon generator was used for animal studies in the 108F Building; it was later moved to LSLII. Monitoring was probably via air sampling, but no information has been discovered yet (ORAUT-TKBS-0006-5, page 35).

Another project involved "milking" thorium-227 from actinium-227 on an ion exchange column. A bioassay procedure was developed specifically for this project under the assumption that the project was going to continue for several years; however, the project ended after only a few milkings. Only a couple of researchers were involved (Bihl, 1995).

Phosphorous-32 was used for biological tracer studies; according to one retired researcher, "pipetting was done by mouth in the old days." Such exposure would be limited to a few researchers and would have to be established through the claimant interview or by some indication of phosphorous-32 bioassay samples in an individual worker's record (ORAUT-TKBS-0006-5, page 35).

6.1.2 *In Vivo* Data Availability

In vivo counting equipment and techniques were developed in the late 1950s and have been in routine use for measuring X-ray and gamma-ray-emitting radionuclides since 1960 (ORAUT-TKBS-0006-5, page 35).

Sometimes radionuclides were listed without a value or detection limit. This probably means a "trace" was found. Additional information is sometimes available on the *In Vivo* Counter Results form if it is included in the worker's personal radiation exposure history file (ORAUT-TKBS-0006-5, page 47).

The radionuclides routinely reported in a database changed over the years. From the beginning of site operations until 1983, sodium-24, potassium-40, cesium-137, and zinc-65 were the only routinely reported radionuclides. In 1983, only potassium-40 and cesium-137 results (or the minimum detectable activity) were routinely reported. In late 1987, cobalt-60 was added (ORAUT-TKBS-0006-5, page 48). As noted below, other less commonly measured radionuclide results are also recorded in the REX database.

6.1.2.1 Whole Body Counters

The first whole-body counter started counting workers in mid-1959 and became routinely used in 1960. It consisted of a single NaI crystal (9.375-inch diameter and 4-inch thick) housed in a counting room (called the Iron Room) with 10-inch thick, pre-World War II steel plates on all six sides and graded shielding on the inner surfaces (lead, cadmium, copper) (Wilson, 1987; Roesch, 1960). The counting geometry was a chair configured to simulate a 1-m arc. The original count time was 20 minutes, which was reduced to 10 minutes in October 1962 (Swanberg, 1962). A second, same-sized NaI detector was added in 1963 (Brady, 1964, page 8).

Shortly after the chair counter in the Iron Room became operational, an entirely new design called the shadow shield counter was developed. The shadow shield consisted of a bed shielded on the bottom and on the sides by lead. The bed moved under a large NaI crystal (11.5-inch diameter by 4-inch thick) that was also shielded by lead, with the exception of the downward-looking face that looked directly onto the body as it passed under the crystal. The shadow shield detector was mounted in a mobile trailer so that it could be moved to areas closer to the Hanford worksites. The trailer also had a thyroid detector and a wound counter. The shadow shield detector became operational in 1963 (Brady, 1964 page 9). The mobile trailer was described as having comparable sensitivity to the larger, conventional whole-body counters installed in massive iron rooms. However, there was some decreased sensitivity in the lower-energy region below about 300 keV, due to increased contribution to the background from scattered radiation (Swanberg, 1963).

A report on the radionuclides detected in workers at the Whole-body Counting Facility in 1961 listed sodium-24, cobalt-60, zinc-65, zirconium-95, niobium-95, molybdenum-99 (presumably molybdenum- 99), technetium-99, ruthenium-103, ruthenium-106, iodine-131, cesium-137, and cesium-144 (Henle, 1962). A similar report summarizing 1961 through 1963 results added scandium-46, chromium-51, and iron-59 to the list (Brady, 1964, page 20).

A shadow shield whole-body detector was installed at the Whole-Body Counting Facility in 1977. This assembly had two 35% GeLi detectors and a 4-inch by 4-inch by 16-inch NaI detector. The shadow shield whole-body detector ended operation in 1987 when the two new counting rooms were added. Wilson (1987) provided a listing of minimum detectable activities that applied to 1980 (ORAUT-TKBS-0006-5, page 37).

By 1978, there were four shadow shield whole-body counters available for use. One was available at the Whole-Body Counting Facility, two in mobile trailers, and one at the Emergency Decontamination Facility; the latter was designated for large acute intakes with potentially high levels of external contamination (ORAUT-TKBS-0006-5, page 37).

A "standup" counter, which began operating in 1983, is still in operation today. It consists of five vertically stacked NaI crystals in a small lead-shielded area. The worker stands in front of the detectors with the detectors to his/her back; the detector array is raised or lowered to best fit the height of the worker. There are four 9.375-inch-diameter-by-4-inch-thick detectors and one 11-inch-diameter-by-4-inch-thick detector, the latter located behind the thoracic region. Count time is 200 seconds (Palmer, no date).

A coaxial HPGe scanning array developed in July 1989 is still in operation today (Lyon, 1990). For this system the person lies on a bed in a shielded room and the detector array moves under the bed.

From 1960 to 1983, four radionuclides were reported routinely: sodium-24, potassium-40, zinc-65, and cesium-137. Potassium-40 is strictly a natural source. Sodium-24 and zinc-65 were detectable in many whole-body counts in the 1960s. Most of these intakes came from sanitary water drawn from the Columbia River (ORAUT-TKBS-0006-5, page 37). Cesium-137 detections are attributable to Hanford operations.

6.1.2.2 Chest Counters

In 1967, Pacific Northwest National Laboratory started using the original large NaI detector in the Iron Room for chest counting, with emphasis on uranium workers. The detector was placed directly over and nearly in contact with the chest region, with the worker in the supine position. Count time was 30 minutes. In the next year, a new counting room called the Lead Room was built specifically for chest counting. The Lead Room had four 5-inch-diameter by 0.375-inch-thick NaI detectors, two in front and two in back of the subject. Count time was 30 minutes (ORAUT-TKBS-0006-5, page 39; Wilson, 1987).

A second chest counting system became operational in 1978 (Wilson, 1987). A phoswich detector became available and was used occasionally for special chest counts, but was never operated on a routine basis. A solid-state germanium counting system using three planar HPGe detectors (soon upgraded to six detectors) replaced the NaI detector in the Iron Room chair counter in 1983 (Palmer, 1984). The HPGe detectors provide better spectral resolution than the NaI detector, thus resulting in lower backgrounds in the region of interest, better discrimination against radon decay products, and better detection of low-energy photon emitters in the presence of large activities of high-energy photon emitters (e.g., cesium-137 or cobalt-60) (ORAUT-TKBS-0006-5, page 40).

Within less than a year, the three-detector system was upgraded to a six-detector array, allowing routine counting times to be reduced to 1,000 seconds with nearly the same reliable detector activities (RDAs) (Palmer, no date; Carbaugh, 1988). In July 1989, a second HPGe detector array became operational in a new shielded cell called the Stainless Steel Room (the inner (i.e., visible) lining of the graded shield was stainless steel). Although intended to be a six-detector array, this counter had only four detectors at first because of operational problems with the detectors. Counting times were increased to 2,000 seconds for the six-detector array and 3,000 seconds for the four-detector array (Lyon, 1990).

Ultrasonic measurements of chest wall thickness for workers who had activity in the lung began in about 1978 and continue today (Palmer, 1979, page 4). Decision levels for non-detected activities use a weight-to-height ratio to estimate chest wall thickness, whereas detected activity is corrected for chest wall thickness using ultrasound (ORAUT-TKBS-0006-5, page 42).

For *in vivo* counting, the assumption was made that thorium-234 was in equilibrium with uranium-238. This was a reasonable assumption at Hanford. Uranium recently separated from dissolved fuel was certainly not in equilibrium, and uranium being treated at the UO_3 Plant might have been in equilibrium depending on how long it had taken the material to go through the separation process and be transported to the UO_3 Plant. However, uranium in this part of the fuel cycle was very soluble and not important in relation to chest counting. Chest counts were used to monitor for intakes of insoluble forms of uranium, which were very old forms in terms of time elapsed since purification from decay progeny (e.g., machining on metal, uranium metallurgy studies) (ORAUT-TKBS-0006-5, page 42).

6.1.2.3 Thyroid Counters

While there is evidence of thyroid *in vivo* bioassay at Hanford as early as 1944 (Ikenberry, 1991), routine thyroid counting started on a limited basis for high-risk workers in 1956. Wilson (1960) states, thyroid counting started on a limited basis for high-risk workers at least as early as 1956. Wilson (1960) states, "At the present time routine thyroid monitoring is conducted on a limited basis in the REDOX and PUREX Facilities. Generally the pattern for coverage in the PUREX Facility includes about four to five employees weekly, picked from the sampling crews, crane operators, and a Radiation Monitor assigned to the stack area. At the REDOX Facility, routine monitoring is accomplished on a weekly basis for the shift crane operators" (Wilson, 1960). The letter continues to discuss counts and other data obtained in 1959; however, there is no indication if those results were placed in workers' files. Radiation monitoring data sheets from 1956 show that results below 10 nCi for iodine-131 were recorded as "less than" (ORAUT-TKBS-0006-5, page 42).

The first mobile whole-body counter had a thyroid counter consisting of a 3-inch by 3-inch NaI detector (assumed to mean 3-inch diameter by 3-inch thick) that was positioned next to the neck. That same detector was included in a description of *in vivo* counting capabilities at the Whole-Body Counting Facility (Andersen, 1971) and again in Palmer (1985). Minimum detectable activities were first listed with corresponding counts in 1986. Because the minimum detectable activity is different for each thyroid count, person-specific calculations were used (ORAUT-TKBS-0006-5, page 42).

Starting at least as far back as 1967, a thin, 2-inch diameter NaI crystal with a beryllium window was used to count iodine-125 in the thyroid. By 1985, thyroid counting for iodine-125 was performed using two intrinsic germanium detectors, with a minimum detectable activity of 0.005 nCi for a 2,000-sec count (ORAUT-TKBS-0006-5, page 43).

Thyroid counting for either of the iodine isotopes has been rare since 1987 (ORAUT-TKBS-0006-5, page 43).

6.1.2.4 Thorium Exposure Monitoring

Experimental work with thorium began as early as 1946 at Hanford and continued until 1970. Except for small-scope, limited-time projects that may have occurred occasionally, exposure to thorium at Hanford stopped in 1970 (Gydesen, 1954; ORAUT-TKBS-0006-5).

Routine monitoring capable of detecting thorium intakes began with the start of the routine whole-body counting program in 1960, and was based on detection of actinium-228. Thorium urinalyses were used for special investigations. Thorium-232 was not routinely reported in whole-body counts, but a prominent actinium-228 peak would have been noticed and investigated (ORAUT-TKBS-0006-5, page 45). The two radionuclides, thorium and actinium, would not have been in equilibrium; both disequilibrium at intake and separate biological processes on the thorium-232 parent and the radium-228 progeny, meaning that the thorium-232 activity in the body would not have been the same as the measured actinium-228 (ORAUT-TKBS-0006-5, page 44). ORAUT-TKBS-0006-5 lists adjustment factors to account for this discrepancy.

6.1.2.5 Head Counters and Other Counts

Miscellaneous counts have been performed over the years at Hanford, including wound counts, head counts, liver counts, lymph node counts, and various longitudinal scans with collimated detectors to pinpoint the location of external or internal contamination. Results of these scans in the REX database are almost always listed as special counts associated with known intakes (ORAUT-TKBS-0006-5, page 47).

Since at least 1978, for intakes of plutonium or americium, head counts have been used to correct chest counts for activity in the bones of the chest region (Palmer, 1979).

Routine head counting for strontium-90 or promethium-147 did occur for some period of time in the 1970s. These counts were not very sensitive and there is the question about what a head count means in relation to the activity in the total skeleton. The same worker should have strontium-90 urinalysis results; the latter would be given preference for confirming or quantifying an intake (ORAUT-TKBS-0006-5, page 47).

6.2 Hanford External Monitoring Data

The following discussion provides a summary of the Hanford site external dosimetry program, as well as the types, quantity, and quality of data that can be used for external dose reconstruction. Details regarding the various analyses used and the associated minimum detectable activities are presented in ORAUT-TKBS-0006-6. Additional information regarding the external dosimetry equipment, methodologies, and techniques in use during the time period of the proposed class is described in the *Manual of Standard Procedures: Personnel Meters* (Hart, 1946). Administrative practices are generally described in *Historical Review of Personnel Dosimetry Development and its Use in Radiation Protection Programs at Hanford,* (Wilson, 1987). A description of the historical recorded dose values is provided in *Historical Hanford Radiological Record Description* (Fix, 2001).

Records of radiation doses from personnel dosimeters worn by workers and co-workers are available for Hanford operations beginning in 1944 and reviews of the Hanford personnel dose data for 10- and 15-year periods from the startup of Hanford are available in Parker (1954) and Keene (1960), respectively. Doses from these dosimeters were recorded at the time of measurement and were routinely reviewed by Hanford operations and radiation safety staff for compliance with radiation control limits.

As is the case with Hanford's internal monitoring data, external monitoring data are available via the CEDR database and the REX database. *The NIOSH External Dosimetry Implementation Guide* (OCAS-IG-001) has identified these records as representing the highest-quality records for retrospective dose assessments.

Historically, Hanford had an extensive Radiation Safety Monitoring program that measured radiation exposure in the workplace by using portable radiation instruments (Howell, 1989), contamination surveys, zone controls, and personnel dosimeters (Parker 1954; Wilson, 1987). Monitoring was performed directly or under the guidance of a specially trained group of radiation monitors (i.e., radiation protection technologists). The results from the personnel dosimeters were used to measure and record dose from external radiation exposure to Hanford workers throughout the history of Hanford operations (Wilson, 1987). These dosimeters, as noted in the Health Instrument Division section of routine reports (ORAUT-TKBS-0006-6), include one or more of the following:

- Personnel whole-body beta/photon dosimeters
- Pocket Ionization Chamber dosimeters
- Personnel extremity dosimeters
- Personnel whole-body neutron dosimeters

Table 6-1 presents the number of annual dose records contained in the REX database for Hanford workers.

Table 6-1: Summary of Available External Monitoring Data for Hanford Workers (1942-1992)
Table 6-1 and corresponding table notes span two pages

	Total Number of Annual External Doses Recorded			
Year	**Total Record Number[1]**	**Shallow Dose Records[2]**	**Deep Dose Records[2]**	**Neutron Dose Records[2]**
1946	4,051	3,220	3,112	0
1947	6,172	4,229	3,962	0
1948	8,668	6,046	4,864	0
1949	8,532	6,035	5,038	0
1950	8,558	5,960	5,109	16
1951	10,701	7,088	5,549	14
1952	10,907	7,281	5,870	1
1953	10,159	7,670	6,763	1
1954	10,636	7,647	6,179	4
1955	12,078	9,287	7,449	2
1956	12,676	8,023	5,466	7
1957	12,450	5,201	4,470	12
1958	10,813	5,419	4,973	307
1959	10,191	4,683	4,192	181
1960	11,015	5,516	5,242	421
1961	11,011	8,101	7,991	455

Table 6-1: Summary of Available External Monitoring Data for Hanford Workers (1942-1992)
Table 6-1 and corresponding table notes span two pages

	Total Number of Annual External Doses Recorded			
Year	**Total Record Number[1]**	**Shallow Dose Records[2]**	**Deep Dose Records[2]**	**Neutron Dose Records[2]**
1962	11,149	9,619	9,582	587
1963	12,219	9,771	9,813	336
1964	12,001	9,905	10,064	918
1965	11,989	9,554	9,654	605
1966	10,848	9,072	9,010	536
1967	11,008	8,450	8,412	395
1968	10,739	8,917	8,630	359
1969	10,311	7,969	6,818	302
1970	11,108	5,509	4,956	206
1971	13,518	6,607	6,217	242
1972	13,404	9,580	9,552	655
1973	13,242	7,650	7,627	548
1974	19,060	9305	9,238	946
1975	20,444	12,273	12,164	471
1976	21,900	11,945	11,866	195
1977	25,589	14,323	14,265	481
1978	27,339	16,495	16,380	495
1979	28,012	16,774	16,250	591
1980	28,019	17,651	16,361	550
1981	28,073	14,802	13,186	571
1982	26,770	14,914	13,150	319
1983	28,092	10,771	7,748	458
1984	29,080	12,063	10,656	605
1985	29,981	10,666	6,977	867
1986	29,679	8,756	5,191	995
1987	24,864	14,217	13,639	1,309
1988	25,261	6,082	5,531	1,572
1989	26,212	9,866	9,260	1,415
1990	28,008	5,252	4,351	1,153
1991	30,595	4,202	3,406	966
1992	36,157	4,320	3,188	948

Notes:
[1] The REX database software does not allow for null entries and inserts a zero where they occur. Therefore, the number of records noted in this column reflects the sum of the zero and non-zero records. Totals shown apply to shallow, deep, and neutron record counts.
[2] Totals shown are for non-zero records.

Hanford began operations in 1944 using in-house dosimeter processing and technical support. Hanford based its beta/photon film dosimetry methods on the dosimeter design developed at the Metallurgical Laboratory by Pardue, Goldstein, and Wollan (Pardue, 1944). This design was implemented at several of the Manhattan Engineer District sites. Beginning in 1944, Hanford implemented its individual worker neutron dosimetry methods, using pocket ionization chambers with a boron-10 enriched lining. In 1950, the Nuclear Track Emulsion Type A dosimeter capability was implemented (ORAUT-TKBS-0006-6).

Parameters concerning Hanford administrative practices significant to dose reconstruction include:

- Policies to assign dosimeters to workers
- Policies to exchange dosimeters
- Policies to record the measured dose and not using a notional dose (i.e., some identified value for lower-dosed workers often based on a small fraction of the regulatory limit)
- Policies to estimate dose for missing or damaged dosimeters
- Policies to replace destroyed or missing records
- Policies to evaluate and record dose for incidents
- Policies to obtain and record occupational dose to workers for other employer exposure
- Policies to evaluate and categorize workplace radiological hazards

Hanford policies appear to have been in place for all of these parameters (ORAUT-TKBS-0006-6). Routine Hanford practices appear to have required assigning dosimeters to all workers who entered a controlled radiation area (Hart, 1967). Dosimeters were exchanged on a routine schedule. Dosimeters were processed and the measured results were recorded and used to estimate dose. There appears to be no use of recorded notional doses, although there are issues of "missed" recorded dose for low-dosed dosimeters, as well as recorded doses for individual dosimeters at levels less than the statistical minimum detection level (see ORAUT-TKBS-0006-6 for details).

Early Hanford dosimetry procedures describe several aspects of the routine dosimetry program. Hanford workers entering operating areas were assigned dosimeters beginning in 1944 and throughout the proposed class timeframe. Trends in the number of monitored workers and the collective dose for these workers are shown in Figures 6-1 and 6-2. These figures illustrate the number of workers with positive recorded dose from photon and neutron radiation, respectively, along with the number of monitored workers (Buschbom, 1993).

Figure 6-1: No. of Monitored Hanford Workers and Collective Dose, 1944 – 1989

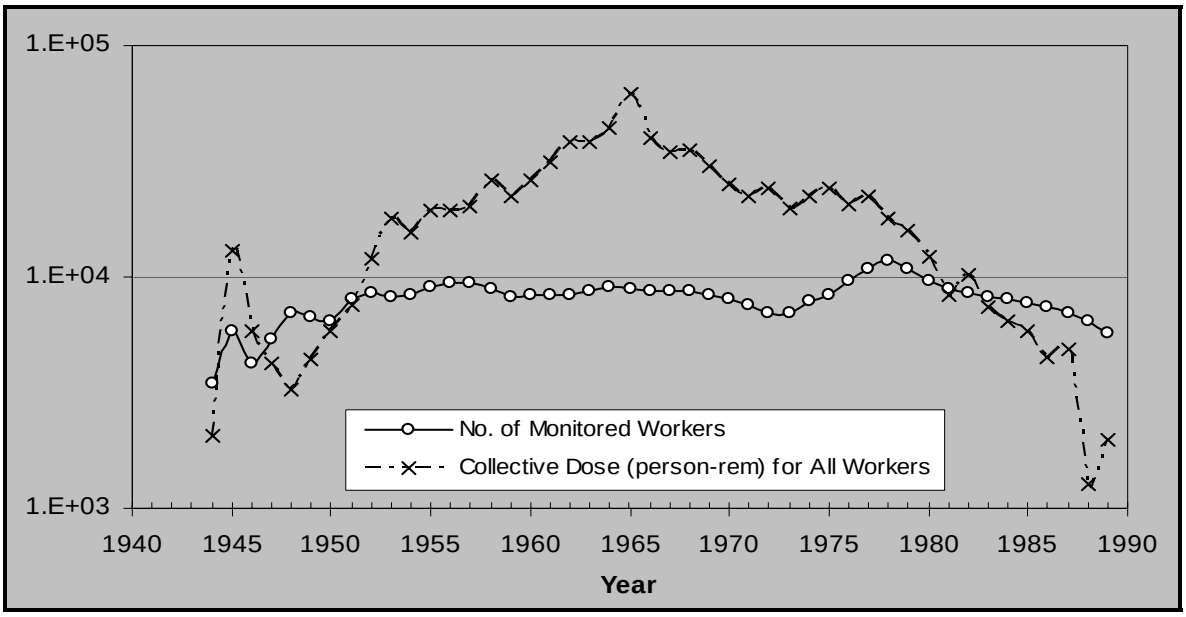
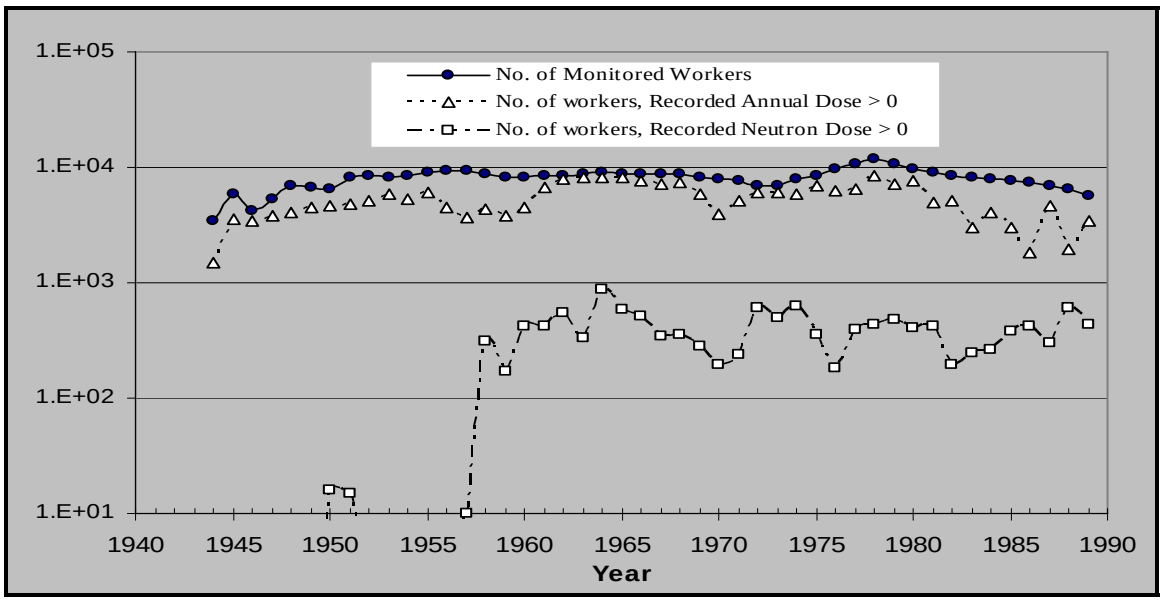


Figure 6-2: Monitored Hanford Workers with Photon >0 and Neutron Dose >0, 1944 – 1989



Administrative practices are generally described in Wilson, 1987. A description of the content of the historical recorded dose values for each year is provided in Fix, 2001. There does not appear to be any significant administrative practice that would jeopardize the integrity of the recorded dose of record. A study of detailed dosimetry records by E. S. Gilbert found agreement between the original paper records and computerized dose records (Gilbert, 1990). In addition, Hanford film dosimeter results were examined in the 1960s at the University of Pittsburgh as part of the AEC Health and Mortality Study of Hanford Workers (AEC, 1966). The University of Pittsburgh research results regarding recorded dose data showed "good quality control was exercised over the film badge

calibration and processing procedures at Hanford over the years (i.e., 1944 through 1961)." In addition, NIOSH has obtained and examined many of the routine weekly and monthly health physics organization reports; these reports illustrate ongoing knowledge of workplace hazards and operational controls.

6.3 Hanford Air Sampling Data

Air monitoring at Hanford was based on gross alpha and gross beta measurements corrected for radon progeny. Air monitoring was typically considered to be a facility-specific activity similar to radiation and contamination surveys and was used in day-to-day administration of workplace activities, such as in the preparation of the Special Work Permits. The raw data, if it still existent, were not collected in a central database, but maintained in facility-specific records. The amount of the raw data still in existence has not been determined.

Limited air sampling results are available from the weekly and monthly reports of the Health Instrument Division of the Medical Department. These are brief summaries, mostly highlighting problems or indicating that air concentrations were below concern. Often no values were given and locations relative to the workers location are unknown. In addition, air sample data from the reactors were almost never listed in these reports.

7.0 Feasibility of Dose Reconstruction for the Proposed Class

The feasibility determination for the proposed class of employees covered by this evaluation report is governed by both EEOICPA and 42 C.F.R. § 83.13(c)(1). Under that Act and rule, NIOSH must establish whether or not it has access to sufficient information either to estimate the maximum radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the class, or to estimate the radiation doses to members of the class more precisely than a maximum dose estimate. If NIOSH has access to sufficient information for either case, NIOSH would then determine that it was feasible to conduct dose reconstructions.

In determining feasibility, NIOSH begins by evaluating whether current or completed NIOSH dose reconstructions demonstrate the feasibility of estimating with sufficient accuracy the potential radiation exposures of the class (discussed in Section 9.0 of this report). If the conclusion is one of infeasibility, NIOSH systematically evaluates the sufficiency of different types of monitoring data, process and source or source term data, which together or individually might assure that NIOSH can estimate either the maximum doses that members of the class might have incurred, or more precise quantities that reflect the variability of exposures experienced by groups or individual members of the class as summarized in Section 7.6. This approach is discussed in OCAS's SEC Petition Evaluation Internal Procedures, which are available at http://www.cdc.gov/niosh/ocas. The next four major subsections of this Evaluation Report examine:

- The sufficiency and reliability of the available data. (Section 7.1)
- The feasibility of reconstructing internal radiation doses. (Section 7.2)

- The feasibility of reconstructing external radiation doses. (Section 7.3)

- The bases for petition SEC-00057-2 as submitted by the petitioner. (Section 7.4)

7.1 Pedigree of Hanford Data

This subsection answers questions that need to be asked before performing a feasibility evaluation. Data Pedigree addresses the background, history, and origin of the data. It requires looking at site methodologies that may have changed over time; primary versus secondary data sources and whether they match; and whether data are internally consistent. All these issues form the bedrock of the researcher's confidence and later conclusions about the data's quality, credibility, reliability, representativeness, and sufficiency for determining the feasibility of dose reconstruction. The feasibility evaluation presupposes that data pedigree issues have been settled.

A centralized radiological records program was established at Hanford at essentially the beginning of operations in 1943. Originally termed the Health Instrument Division, and in later years the Hanford Personnel Dosimetry Program (HPDP), this centralized group has maintained responsibility for Hanford workers' radiological records, as well as for operating the internal and external dosimetry programs. There have been only two primary Hanford contractors and predecessor agencies responsible for the HPDP during the proposed class timeframe. Since 1965, the HPDP has been administered by the Pacific Northwest National Laboratory. Prior to Pacific Northwest National Laboratory, the General Electric Company was the administrator. DOE and its contractors have required radiological dose records to be administered and preserved by the HPDP for all Hanford workers and visitors, past and present, and have provided specified and requested reports using these records. The HPDP also maintains historical documentation of Hanford contractor radiation protection policies. However, facility radiological records, such as measured ambient exposure or contamination levels, are typically maintained according to the specific facility and are not included in the radiological record system for Hanford workers.

Hanford record-handling capabilities have evolved over time with the availability of computer-assisted retrieval and record imaging technology. Prior to 1958, HPDP staff used forms to manually record dosimeter processing and dose information. These forms were revised for each year of operation to show the scheduled dates of dosimeter exchange for each operating area. Designations on the form show each area that was operational during each year. Forms were revised to include designations for each new operating area as it became operational.

Since 1958, the Hanford HPDP has migrated historical monitoring records into the newer systems while preserving existing original, manually-recorded records. Currently, a sophisticated database system is used to track and report dose for all current workers. The program also maintains a REX system that contains individual radiological exposure records for all Hanford DOE, contractor, and subcontractor employees, as well as for Hanford visitors. The REX database also contains annual summaries of each worker's external dose for each year of Hanford employment and summaries of internal dose for Hanford workers.

HPDP staff members maintain individual worker exposure records that are not reducible to database elements and also maintain backup documentation, known as the Hanford Radiation Protection Historical Files. To support this effort, the REX system incorporates exposure documentation on

microfilm and compact disc that is indexed into computer-assisted retrieval systems. The computer-assisted retrieval systems allow rapid retrieval of documents for any worker, using identifiers such as payroll number, social security number, names, and/or REX identifiers. REX identifiers are unique numbers generated for each worker to link all of his/her records. The staff scans, indexes, and retrieves hard-copy documents; prepares documents for long-term storage; and tracks and accounts for the documents through the imaging and indexing process.

Current and past Hanford workers have access to their records at any time upon request. Records supplied to NIOSH by Hanford's HPDP staff for EEOICPA purposes include computerized printouts of worker dose, in addition to copies of original, manually-entered dose records (when applicable).

7.1.1 Internal Data Review

NIOSH has found that Hanford policies for the collection and maintenance of employee monitoring data are sufficient for dose reconstruction in terms of the pedigree parameters described above. Upon request, the Hanford HPDP provides original hardcopy records in addition to database printouts (prior to 1958), which ensure the ability to confirm data. Per Dose Reconstruction Training ORAUT-TRNG-0051, dated March 1, 2007, personnel performing dose reconstructions compare these data when performing dose reconstructions. Having the original records and this procedure in place negates a need for a separate internal consistency check of the manually entered data.

7.1.2 External Data Review

As noted for internal dosimetry records, Hanford policies also appear to have been in place for all significant external dosimetry record collection and maintenance activities, resulting in records of sufficient pedigree for external dose reconstruction use. In addition to NIOSH's review, a 1990 evaluation of the Hanford program identified no significant administrative practice that would jeopardize the integrity of the recorded external dose (Wilson, 1990). Two additional reviews of external dose records have been conducted. A study of detailed dosimetry records for a selected group of workers included in the Hanford Mortality study (Gilbert, 1990) found very good agreement between original paper records and Hanford's REX database. A study by the University of Pittsburgh, *Feasibility Study of the Correlation of Lifetime Health and Mortality Experience of AEC and AEC Contractor Employees with Occupational Radiation Exposure* (AEC, 1966), concluded that good quality control was exercised over the film badge calibration and processing procedures at Hanford over the years covered by the proposed class.

7.2 Internal Radiation Doses at Hanford

The principal sources of internal radiation doses to members of the proposed class would have been inhalation and ingestion of radiological contamination during the following operations:

- Fabrication of uranium metal fuel elements
- Irradiation of fuel elements in reactors to produce plutonium-239
- Chemical separation of plutonium-239 from irradiated fuel elements

- Plutonium concentration and finishing
- Research and Development of production operations and biological and ecological systems
- Waste management operations supporting all site radiological activities

The potential internal sources would have been dependent on the operational area and activities. The major sources of intakes have been plutonium, americium-241 (either as an ingrown contaminant in the plutonium or as a separated waste product), uranium, fission and activation products, and tritium. However, the records list a wide spectrum of radionuclides that were monitored and an even longer list of codes used to identify the radionuclides, groups of radionuclides, specific measurement techniques, or combinations of radionuclides and techniques. Many of the radionuclides apply to a small set of workers on a research project or to workers (for instance, radiation monitoring technicians) whose tasks could have exposed them to many different sources (ORAUT-TKBS-0006-5).

7.2.1 Process-Related Internal Doses at Hanford

The following subsections summarize the extent and limitations of information available for reconstructing the process-related internal doses of members of the proposed class. More detailed information on the individual topics can be found in Section 6.1 of this report and in ORAUT-TKBS-0006-5.

7.2.1.1 Plutonium

Plutonium production was the original mission of the Hanford Engineer Works; plutonium bioassay was recognized as a priority from the very beginning of operations. A special studies group was formed in 1944 to determine a way to measure plutonium in the body. Limits on the amount of plutonium in the body were set as early as 1944. After experimentation with various methods of plutonium bioassay analysis, routine urine sampling plutonium was initiated sometime prior to September 1946 (Wilson, 1987).

Based on information in ORAUT-TKBS-0006 and its associated references, the recorded plutonium internal dose to Hanford workers is reasonably accurate for all years and for all facilities. In addition, a guidance document written by J. W. Healy, dated March 1, 1946, shows that all Hanford workers entering plutonium areas were to have been placed in the plutonium urinalysis bioassay program. The guidelines to determine which workers were subject to plutonium urinalysis included (Healy, 1946):

> *The workers of the Plant will be divided into three classes, depending on their relative exposure to Plutonium. The frequency of analysis for each class will be given as follows:*
>
> - *Class 1 – Continuously employed in product work area – every 2-3 months*
> - *Class 2 – Occasionally employed in product work area – every 4-6 months*
> - *Class 3 – All other employees (for control) – every 12 months*

The policy was modified in a 1948 document (Healy, 1948):

- *Group 1 consisted of personnel who spent 50% of their working time in product (plutonium) areas of the Isolation Building, Concentration Buildings, or the Control Laboratories; they were sampled every three months.*

- *Group 2 consisted of personnel working in the 200 Areas who spent 50% of their working time in the Canyon Buildings and/or Metal Storage Basins and the technical personnel in the 300 Area working with product on an intermittent basis; they were sampled every six months.*

- *Group 3 consisted of personnel who had clearance to any zone of the operating areas but did not spend 50% of their time in a product zone; they were sampled once a year.*

- *In addition, samples were taken from personnel involved in an accident involving possible plutonium contamination.*

Bioassay results are available from the start of routine sampling continuing throughout the time period of the class proposed for this evaluation. The quantity and quality of available plutonium urinalysis results in REX were sufficient for NIOSH to perform co-worker intake analyses presented in ORAUT-OTIB-0039. NIOSH has found no indication of the existence of any work groups that were at risk for plutonium intakes that are not represented in the co-worker data. NIOSH has not identified any additional data that would indicate that the co-worker data does not adequately represent the exposure potential of Hanford's high risk plutonium workers.

Based on the information available to NIOSH, the internal dose from plutonium for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.1.2 Americium

Americium was usually a trace contaminant in plutonium mixtures; however, there were processes at Hanford that involved separating americium from plutonium. Experiments to separate americium-241 from aged plutonium solutions were carried out as early as 1949 (Hanford Works, 1949). The separation by the peroxide precipitation method was accomplished in November 1950 in the Isolation Building (231-Z); the quantity of americium obtained far exceeded the amount anticipated. After the americium was precipitated in the Isolation Building, it was then concentrated in a recovery unit of the Plutonium Finishing Plant (234-5Z) (Various Division Managers, 1950; Gerber, 2005). Hanford monthly reports from 1951 to 1953 show the quantities of americium-241 produced to be in the tens of milligrams to about 1 gram per month.

In 1964, a new americium recovery system was installed in a glovebox in the Waste Treatment Facility (242-Z), part of the Plutonium Finishing Plant complex. The 242-Z americium recovery system became operational in May 1965, producing americium nitrate. Production was increased from the early processes with the first batch on September 9, 1964 yielding 7.6 grams. In June 1965, 8.6 grams were recovered, 15.2 grams in October 1965, and 8.3 grams in December 1965. From 1966 through 1968, the rate of production averaged 7 to 8 grams a month. Production rates dropped in 1969 due to a decrease in available plutonium feed (Gerber, 2005).

In 1969, the process in 242-Z was converted from a batch to a continuous process, which increased the purity and concentration of the americium product (DOE, 2002). On August 30, 1976 in the 242-Z Facility, an explosion occurred in a column containing about 100 grams of americium-241. Although the column was located in a glovebox, the chemical operator standing in front of the column was contaminated and suffered facial cuts, burns, eye damage, and americium-241 deposition. Following the accident, the 242-Z facility was closed permanently (Gerber, 2005).

NIOSH has found no indication of americium excreta analysis being performed at Hanford prior to 1964. There is no mention of americium analysis either in Healy (1948); in a 1954 memo, "Bioassay Annual Report," that lists numbers of urinalyses for plutonium, fission products, and uranium (Watters, 1954); or in a compilation of bioassay procedures, titled "Bioassay Procedures and Analysis (Old Bioassay Bible)," dated April 10, 1961 (Unknown author, 1961).

The first americium bioassay records in the REX database show 41 urinalyses for americium-241 in 1964, collected from 19 workers. The samples were collected over a short time period. The first 12 samples were collected on August 25 or 26, 1964. The last sample was collected on October 29, 1964. These samples appear to be baseline data for the new process starting up in 242-Z. Since no americium urinalyses were recorded in 1965 or 1966, it appears routine sampling for americium separation workers had not yet started. An interviewee (the manager of the Radiobioassay laboratory at that time) stated that "From 1965 to 1983, americium and curium were obtained by DDTP extraction, collection on a planchet, and gross alpha counting" (Personal Communication, 2003). The earliest located information on the minimum detectable activity on the analyses dates from 1967, as described below.

For 1967, the REX records show 168 bioassay analyses; these were a combination of urine and fecal analyses for the same six workers who were involved in a potential intake accident on May 2, 1967. There are internal dosimetry evaluations in the workers' files documenting the accident and bioassay results. Many of the urine sample results were listed as $<5.41 \times 10\text{-}7$ μCi/L, so it is assumed that this was the minimum detectable activity for the analysis (ORAUT-TKBS-0006-5).

In a memorandum to file from a senior development engineer in the Personnel Dosimetry Services, the new detection limit for americium-241 is stated as 2.0 dpm/sample as of July 10, 1969 (Jech, 1969).

From 1968 through 1990, americium bioassay results are found in the REX database. In addition, routine *in vivo* chest counts for plutonium and americium deposited in the lung were initiated in early 1968. The Chest Counting Room was constructed using lead with copper sheeting, and used four five-inch diameter sodium iodide (NaI) crystals coupled in five-inch phototubes. This analysis had a detectable amount of 0.15 to 1.60 nanocuries (Wilson, 1987).

Based on the initiation of routine *in vitro* bioassay for americium in January 1968, and the routine operation of the chest counter for the detection of americium in early 1968, NIOSH finds that the internal americium-241 dose for the class under evaluation can be reconstructed with sufficient accuracy beginning in 1968. However, prior to January 1, 1968, based on the lack of available information showing that there was a routine americium bioassay program in place, or information detailing the type of analysis of levels of detection, NIOSH finds that the internal americium-241 dose

cannot be reconstructed with sufficient accuracy for the few areas where americium activity cannot be associated with measured plutonium activity. This limitation affects potential exposures in the following facilities where americium isolation activities took place: the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z).

7.2.1.3 Uranium

Routine urinalysis for uranium began in 1947, but the results were considered unreliable until 1948 when improvements in the procedure were made (Healy, 1948). The numbers of uranium urinalysis results in the REX database were found to be sufficient for performing co-worker intake analyses on a quarterly basis through 1969, and on an annual basis through the 1970s. The number of results per period ranged from a low of 65 in 1973 to a high of 1,197 in the second quarter of 1955. NIOSH has found no indication of the existence of any work groups that were at risk for uranium intakes that are not represented in the co-worker data, and NIOSH has not identified any additional data that would indicate that the co-worker data set does not adequately represent the exposure potential of Hanford's highest risk uranium workers. A method to apply uranium co-worker data to unmonitored workers can be found in ORAUT-OTIB-0039, Section 6.2.

NIOSH finds that uranium co-worker intake results cannot be extrapolated to cover exposures occurring prior to 1948, due to major process differences existing prior to the urinalysis monitoring program. Starting in January 1945, Hanford began extruding uranium billets in Building 314. The extrusion process entailed heating a uranium billet to about 1000 degrees C in a muffle type furnace to soften the metal, and then forcing the billet at high pressure through a die to form uranium rods approximately 1.45 inches in diameter (Lindlief, no date; Gerber, 1993; DOE, 1997). Hanford ended the extrusion process in 1948, at about the same time that uranium urinalysis began (DOE, 1997). Accordingly, there is not a predictable relationship between exposures prior to 1948 and exposures thereafter that were associated with entirely different processes. However, because of similarities between the Hanford extrusion process and the processes at several AWE uranium metal handling facilities, NIOSH can adequately bound the doses from Hanford uranium metal operations using assumptions and methods such as those provided in ORAUT-OTIB-0004.

Based on the information available to NIOSH, the internal dose from uranium for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.1.4 Thorium

As early as October 1945, Hanford performed experimental work and testing with thorium (called "myrnalloy" at the time) (Gydesen, 1954; McMaster, 1951). In January 1946, Hanford received a shipment of 150 pounds of thorium, which consisted of crooked four- to five-foot long rods that required straightening prior to machining (Gydesen, 1954). To prevent the rods from being contaminated with uranium from the contaminated equipment in Building 314, these thorium rods were straightened manually in the 300 Area Maintenance Shop with a 75 ton press. This shop was possibly located in Building 3722 (known later as the "Area Shop") or the Tool Room Shop inside Building 313. Following straightening, the rods were cut into 33 slugs with a power hack-saw, then machined on a small lathe in the 313 Tool Room (Kidder, 1946). The slugs were then canned, welded, and tested for integrity. Prior to charging them into a production reactor, some of these 33 slugs were placed in the 305 Test Reactor to determine their effect on neutron flux distribution. On

March 26, 1946, these thorium slugs were charged into the 105 D Reactor for testing. In April 1947, 171.2 additional pounds of thorium rods were received at Hanford and were machined into 44 slugs (Gydesen, 1954).

Large-scale thorium contamination was introduced into the 313 Building and surrounding fuel warehouses in the early 1950s. Thorium work in Building 313 continued until l970.

Thorium work (See Table 7-1 below) was also conducted in Building 306 (alloy and fabrication test and development) from 1956 through 1970; Building 3706 (radiochemistry in support of fuel fabrication) from 1954 through 1963; Building 3732 (fabrication of thorium oxide fuel targets and a furnace for recycling depleted thorium) from 1965 through 1970; Building 3722 (possible machining of thorium rods in the early years, and later the fabrication of pelletized fuel targets) from 1946 through 1970; and the 202 A PUREX Building (thorium recovery from irradiated fuel elements) with a process test in 1965 and two major thorium campaigns in 1966 and 1970. The PUREX thorium work recovered approximately 565 tons of thorium in the nitrate form from both campaigns (ORAUT-TKBS-0006-5; Gerber, 1992; Walser, 1978).

Table 7-1: Buildings with Thorium Processing

Building, Area	Date
313, 300	1946–1970
306, 300	1956–1970
3706, 300	1954–1963
3732, 300	1965–1970
3722, 300	1968–1970
202 A, PUREX, 200 East	1965–1970

The sources for Table 7-1 include ORAUT-TKBS-0006-5 and Gydesen 1954.

Routine monitoring for thorium intakes by whole-body counting was based on actinium-228. NIOSH has found that whole-body count records may report either thorium-232 results or actinium-228 results, but in either case the measured activity was actinium-228. ORAUT-TKBS-0006-5 presents methods and assumptions for assigning thorium intakes based on actinium *in vivo* bioassay results. Whole-body counting equipment and techniques were operational at Hanford in 1959 and have been in use for routine bioassay since 1960 (ORAUT-TKBS-0006-5, page 35).

Examination of Hanford *in vivo* and *in vitro* bioassay records indicate insufficient thorium bioassay prior to the start of routine whole-body counting in 1960. Available thorium specific workplace and air monitoring data were also found to be inadequate to support sufficiently accurate dose reconstruction prior to 1960.

Based on the inadequacies of thorium specific monitoring prior to the start of the routine whole-body counting program in 1960, NIOSH finds that the internal dose from intakes of concentrated thorium activity cannot be reconstructed with sufficient accuracy prior to January 1, 1960. Accordingly, NIOSH finds that sufficiently accurate reconstruction of internal thorium dose is not feasible for workers employed in Buildings 313, 306, 3706, and the 3722 Shop, prior to January 1, 1960.

ORAUT-TKBS-0006-5 presents methods and assumptions for reconstructing thorium dose in areas where no thorium isolation occurred, such as other 300 Area facilities handling uranium. Levels of thorium exposures in these locations can therefore be associated with monitored uranium exposures. If building information is not available and there is evidence that a person worked with uranium in the 300 Area, 1946-1970, ORAUT-TKBS-0006-5 states it is favorable to claimants to assume exposure to thorium.

7.2.1.5 Tritium

Bioassay monitoring for tritium began in 1949 at Hanford (ORAUT-TKBS-0006-5). As was the case at many facilities, tritium doses were included in the external dosimetry reports, through 1987. Tritium dose reconstruction is possible from 1949 to the present day based on individual worker monitoring and through the assignment of co-worker doses for unmonitored workers. ORAUT-TKBS-0006-5 provides a method to assign tritium exposures to unmonitored workers based on a co-worker analysis. NIOSH has found no indication of the existence of any work groups that were at risk for tritium intakes that are not represented in the co-worker data, and NIOSH has not identified any additional data that would indicate that the co-worker data do not adequately represent the Hanford workers with the highest tritium exposure potential.

At the current time, little information on the use of tritium at the site prior to 1949 has been found. Facility 108-B started tritium extraction operations in 1949. An extensive search of site records yielded no documents mentioning tritium or its code name, P-10, dated earlier than 1948. This indicates that the tritium programs were likely to have begun in 1949. Prior to this, tritium may have been present at the 100 Area reactors, or at the 200 Area Plutonium Separations Facilities, but NIOSH has found no indication that tritium was isolated and separated, and thus would not be a significant dose contributor. ORAUT-TKBS-0006-5 provides a method to assign tritium exposures to unmonitored workers prior to 1949 that results in a dose value larger than all but a few recorded doses from 1949 through the 1960s when tritium was isolated and separated.

Based on the information available to NIOSH, NIOSH finds that it is feasible to estimate the internal dose from tritium with sufficient accuracy for the class under evaluation.

7.2.1.6 Fission Products

Exposure to fission and activation products was monitored by combinations of workplace/personal surveys, air sampling, and/or bioassay. Fission product urinalysis began soon after the Hanford bioassay group was formed in 1946; however, the analytical method used was considered erratic and unreliable until January 1948. After 1948, the urinalysis procedure still did not account for all fission product nuclides, but only separated and counted radionuclides of alkaline earths and rare earths, such as strontium, yttrium, barium, lanthanum, cerium, europium, promethium, zirconium, and niobium. It did not account for radionuclides such as ruthenium, cesium, zinc, cobalt, or manganese. The records do not have sufficient information to link the results of the monitoring to specific radionuclides, since the analyses were usually gross beta or gross gamma counts and were recorded as “fission products” under a variety of names (ORAUT-OTIB-0054). Fission product urinalysis was used to monitor for intakes of fission products until the implementation of whole-body counting in 1960.

To account for exposures from all plausible nuclides, ORAUT-OTIB-0054 provides a method for using intake mixture ratios, based on different types of work or facilities, to account for nuclides not specifically analyzed. For example, if an intake of strontium-90, cesium-137, or ruthenium-106 was being assigned to a worker, the other fission and activation products can be assigned by a ratio based on the type of work or facility. At Hanford, some fission products had greater prominence than indicated in ORAUT-OTIB-0054; these included zinc-65 for essentially all workers (because of its presence in the Richland drinking water through about 1972), sodium-24 for workers at the once-through-cooled production reactors through about 1971 (see Section 5.3.1), europium-154 for workers at N Reactor (because of the samarium-ball emergency shutdown system), and sodium-24 for 400 Area workers (FFTF) for 1980 through 1994. From 1960 to present, these radionuclides have been measured by whole-body counts. If their activity is not included in the whole-body count record, the standard missed dose procedure for assigning these intakes with minimum detectable activities is used.

Cesium-137 was recorded routinely with every whole-body count from 1960 through 1983. For 1984 to 1988, with a few exceptions, cesium-137 was recorded only if it was detected above a reporting level. Because of its long half-life, and abundance in waste from the Separations Plants, cesium-137 has long been considered one of the principal contaminants at Hanford and has often been used as an indicator of potential intakes.

ORAUT-OTIB-0039 provides guidance to assign intakes prior to whole-body counting in 1960 and for unmonitored workers, based on co-worker data intake levels during the periods of the highest plutonium production years at Hanford from 1965 through 1967 (DOE, 1996).

Bioassay results are available from the beginning of routine sampling continuing throughout the time period of the class proposed for this evaluation. The quantity and quality of available fission bioassay results in REX was sufficient for NIOSH to perform co-worker intake analyses, which are presented in ORAUT-OTIB-0039. ORAUT-OTIB-0054 can be used to account for nuclides which were not directly analyzed for in the gross alpha and beta analyses. NIOSH has found no indication of the existence of any work groups that were at risk for fission product intakes that are not represented in the co-worker data. NIOSH has not identified any additional data that would indicate that the co-worker data do not adequately represent the exposure potential of the Hanford workers with the highest risk for exposure to fission products.

Based on the information available to NIOSH, NIOSH finds the internal dose from fission products for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.1.7 Iodine

Considerable numbers (hundreds per month) of thyroid scans for iodine-131 were performed on workers in the fuel dissolution (canyon) buildings during 1945 through at least 1946. In addition, Wilson (1960) states, “At the present time routine thyroid monitoring is conducted on a limited basis in the REDOX and PUREX Facilities.” The letter continues to discuss counts and other data obtained in 1959; however, there is no indication if those results were placed in workers’ files. Radiation monitoring data sheets from 1956 show that results below 10 nCi for iodine-131 were recorded as “less than.” The presence of iodine-131 would have been detected in a whole-body count, but the

recorded quantity would have been based on a whole-body calibration, not a thyroid calibration (ORAUT-TKBS-0006-5).

A review of the thyroid monitoring program was conducted for the Hanford Environmental Dose Reconstruction Project (Ikenberry, 1991). The Ikenberry document, which discusses the review of the thyroid monitoring program, reviewed over 7,900 thyroid checks from October 1944 through August 1946. The tolerance level for iodine-131 in air had been established in October 1945 as 1×10^{-13} Ci/cm^3 (Cantril, 1945) based on a permissible equilibrium amount in the thyroid of 2 μCi. The routine scanning program began in late May or early June 1945. The decision level for the measurement was estimated to correspond to a thyroid burden of about 27 nCi, and 93% of the measurements were below this activity. The highest measurement considered to be reasonably due to a thyroid burden (as opposed to external contamination) was 131 nCi (ORAUT-TKBS-0006-5). In these data, there are preponderances of low net count-rate results. Over 36% of the results were 0 cpm and nearly 80% were less than 5 net cpm. Since the normal background count rate was reported as being about 20 cpm, more than 98% of all results are within a factor of two of normal background (20 net cpm). Ninety-three percent of all measurement results were at or below the decision limit of 10 net cpm (ORAUT-TKBS-0006-5).

Since the beginning of routine whole-body counting, detections of iodine-131 have been a rare occurrence. For instance, from 1962 through 1969 (the peak production years), only about 130 workers (out of about 14,500 whole body and thyroid counts) had detectable iodine-131; results ranged from 0.001 to 560 nCi, the highest measurement being a same-day measurement after an accidental exposure in the T Plant canyon. Ninety percent of the detected results were less than 15 nCi.

ORAUT-TKBS-0006-5, Section 5.6, provides guidance for assigning iodine-131 intakes. For workers prior to routine whole-body counting, a claimant-favorable assumption is made in which all at-risk workers are assumed to have thyroid burdens of 30 nCi (a daily intake of 20,000 pCi). NIOSH has found no indication of the existence of any work groups that were at a higher risk for iodine exposures than those workers that were included in the whole-body counting program from 1960 to 1987. From 1960 to 1987, NIOSH assumes that workers who were not covered by whole-body counting did not incur intakes greater than the thousands of workers given whole-body counts, which showed no detection. Using a nominal detection limit for whole-body counts (as opposed to more sensitive thyroid counts) of 5 nCi, unmonitored workers associated with reactors or Fuel Dissolution Plants would be assigned iodine-131 intakes of 3400 pCi/d. Because there was no significant source term after 1987 (the reactors were shut down by that time), no intakes of iodine-131 would be assigned after 1987 unless the worker's personal information indicates the potential for an exposure, such as might be associated with a research project (ORAUT-TKBS-0006-5).

Based on the information available to NIOSH, the internal dose from iodine for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.1.8 Polonium

Starting in 1945 and continuing into the early 1950s, bismuth slugs were irradiated in Hanford reactors to produce polonium-210; however, it appears that the slugs were promptly shipped offsite (Tilley, 1945; DOE, 1997) for processing at the Monsanto facility in Ohio. No evidence has been

found that routine extraction or handling of concentrated polonium-210 occurred at Hanford during these early years.

There are indications that work with pure polonium-210 occurred in the 308 Building in 1968 and again in 1975 (ORAUT-TKBS-0006-5). Whether the work in the 308 Building was continuous throughout that period or occurred just in those two years is not known, but bioassay data from the REX database (see Table 7.2) span several years surrounding those two years, indicating that the work took place over several years. These results include both urine and fecal samples. It appears that polonium work was initiated sometime prior to 1968, based on a handwritten note documenting a telephone conversation in November 1967, during which it was stated that the polonium-210 starts in the process as the soluble form, but is converted to the insoluble form (Henle, no date).

Table 7-2: Count of Polonium Bioassay Results (as obtained from REX)

Year	Number of Polonium Results
1968	220
1969	91
1970	0
1971	1
1972	20
1973	0
1974	3
1975	4
1976	18
1977	23
1978	26
1979	22
1980	1
1981	1
1982	0
1983	12

Due to the limited scope and localized nature of the polonium isolation work, it is considered unlikely that a group of workers exists that would have had a higher exposure potential than the workers included in the polonium monitoring program. Polonium doses to unmonitored workers in the 308 Building can be bounded by applying claimant favorable assumptions and methods such as those provided in the NIOSH guidance document, *Analysis of Coworker Bioassay Data for Internal Dose Assignment* (ORAUT-OTIB-0019). Based on the information available to NIOSH, the internal dose from polonium for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.1.9 Uranium-233

Results of analyses performed specifically for assessing uranium-233 exposures are very limited. However, NIOSH finds that doses resulting from uranium-233 exposure can be estimated with sufficient accuracy using methods detailed in ORAUT-TKBS-0006-5 and ORAUT-OTIB-0039. A brief summary of the Hanford activities involving uranium-233, the monitoring and analyses performed, and the dose reconstruction process available are presented below. Complete details are provided in the aforementioned documents.

Uranium-233 was isolated from irradiated thorium at PUREX from 1966 to approximately 1971. Separation of uranium-233 from thorium occurred in three distinct campaigns: a small process test in 1965, production runs in 1966, and production runs in 1970. A total of 820 kg of uranium-233 was produced (Walser, 1978; Isochem Inc., 1967). See Section 5.3.4 of ORAUT-TKBS-0006-5 for a discussion of the program to create uranium-233 by irradiation of thorium. Operators, radiation monitors, and equipment maintenance workers at PUREX involved in the campaigns might have had the potential for intakes without monitoring that was specific for uranium-233.

The REX database shows that a few urinalyses were obtained specifically for uranium-233, mostly in 1970. No information has been located regarding how the analyses were performed or the units of the recorded results (see Subsection 6.1.1.5).

For the purposes of reconstructing doses associated with uranium-233 exposure, ORAUT-TKBS 0006-5 uses the highest uranium-233 urinalysis result available to NIOSH to estimate potential chronic intakes for the period 1965 through 1970. Because the material was absorption type F, urinary excretion equilibrates quickly; thus, the same daily intake can be applied for 1 to 5 years chronic exposure. The daily intake derived from the highest urinalysis result available is shown to be 16 pCi per day (ORAUT-TKBS-0006-5). To ensure claimant favorability this conservative daily intake rate can then be assumed for the entire period of potential uranium-233 exposure. Section 5.2.5 of ORAUT-TKBS-0006-5 lists the contaminants that need to be added to this intake.

Based on the information available to NIOSH, the internal dose from uranium-233 for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.2 Ambient Environmental Internal Radiation Doses at Hanford

ORAUT-TKBS-0006-4 and ORAUT-PROC-0060 provide the rationale, historical background, and data for reconstructing occupational environmental doses for unmonitored personnel at the Hanford site. Internal dose from the inhalation of radioactive materials may be determined from radionuclide air concentrations. ORAUT-TBKS-0006-4 describes the main potential sources of dose that could be received by an individual while outside Hanford operational facilities.

7.2.3.1 Estimating Intakes from Airborne Radionuclides

NIOSH uses the RATCHET computer program to calculate intakes from airborne radionuclides. The source terms were provided by the RAC report (2002), which describes methods for calculating "worst case" radiation doses from short-lived gaseous radionuclides and radioactive particles that were released to the atmosphere during Hanford operations from 1944 through 1961. The RAC (2002) source terms were based on the extensive research performed by Heeb (1994) as part of the Hanford Environmental Dose Reconstruction Project (HEDR), a 1990s study estimating the radiation dose that individuals could have received as a result of radionuclide emissions from 1944 to 1992 at the Hanford site.

RAC (2002) provides monthly release estimates for the period from Hanford startup in 1944 through 1961. These files were extended to Hanford facility shutdown dates using the data from Heeb (1994) and augmented with the revisions to the iodine-131 releases by Napier (2002). Minor releases in the 1980s were added as reported in the Hanford annual reports for those years. The argon-41 source

terms for the reactors, taken from RAC (2002), were respectively extended through the date when each reactor was shut down using the approach in that report. The plutonium-239 releases from the Z Plant were also extended using the 2-month lag-time approximation of RAC (2002). Details regarding inputs into the RATCHET program (uncertainties, dispersion factors, receptor locations, etc.) can be found in Section 4.2 of ORAUT-TKBS-0006-4.

The following radionuclides were evaluated:

- Argon-41
- Cerium-144, Promethium-144
- Cesium-137, Barium-137
- Hydrogen-3
- Iodine-131, Xenon-131m
- Plutonium-239
- Ruthenium-103, Rhodium-103m
- Ruthenium-106, Rhodium-106
- Strontium-90, Yttrium-90
- Zirconium-95, Niobium-95

Annual emissions were evaluated for the following sources:

- T Plant particles, B Plant particles, Z Plant particles, REDOX Plant particles, PUREX Plant particles
- T Plant iodine, B Plant iodine, REDOX Plant iodine, PUREX Plant iodine
- B & C Reactor noble gas, KE & KW Reactors noble gas, N Reactor noble gas, D & DR Reactors noble gas, H Reactor noble gas, F Reactor noble gas
- 108-B elemental tritium

The annual air concentrations computed by RATCHET are multiplied by 2,400 m^3/year, which is the recommended breathing rate by reference man doing light work of 1.2 m^3/hour times a use factor of 2,000 hour/year (ORAUT-TKBS-0006-4). A standard deviation of 0.4 m^3/hour was assigned to this breathing rate. The final intake results provide the annual intakes in becquerels per year for the maximum median receptor location by year and by radionuclide. Table 7-3 lists the maximum intake values by radionuclide given in ORAUT-TKBS-0006-4, Table A-12.

Table 7-3: Maximum Intakes by Radionuclide	
Radionuclide	**Maximum intake (Bq)**
Cerium-144	6.64E+01
Cesium-137	2.35E+00
Hydrogen-3	1.15E+05
Iodine-131	1.04E+05
Plutonium-239	1.47E-02
Ruthenium-103	5.84E+02
Ruthenium-106	1.93E+02
Strontium-90	2.67E+00
Zirconium-95	7.92E+01

Using this method, NIOSH finds that the internal dose from environmental sources for the class under evaluation can be reconstructed with sufficient accuracy.

7.2.3 Internal Dose Reconstruction Feasibility Conclusion

NIOSH has established that it has access to sufficient information to either estimate the maximum internal radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the class; or estimate the internal radiation doses to members of the class more precisely than a maximum dose estimate, with the exceptions of : the americium-241 internal dose from January 1, 1949 to December 31, 1967 for the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z); and the thorium-232 internal dose from September 1, 1946 to December 31, 1959 for the Metal Fabrication Building (313), the Reactor Fuel Manufacturing Pilot Plant (306), the 300 Area Maintenance Shops (3722), and the Radiochemistry Laboratory (3706).

7.3 External Radiation Doses at Hanford

The principal sources of external radiation doses for members of the proposed class are those associated with nuclear reactor fuel fabrication, nuclear reactor operations, the radiochemical separation/refinement/finishing/storage of plutonium, and the handling of radioactive waste. Other processes such as research, development, and testing, or processes limited to a specific radionuclide product, also contributed to worker exposures (although to a lesser degree). The processes that generated the principal sources of external radiation dose are described both in Section 5.0 of this document and in ORAUT-TKBS-0006-2.

7.3.1 Process-Related External Radiation Doses at Hanford

The following subsections summarize the extent and limitations of information available for reconstructing the process-related external doses of members of the proposed class.

7.3.1.1 Radiation Exposure Environment

The external dose received by workers at Hanford was a function of the physical location of the workers on the site, the processes taking place, the types and quantities of material present, and the

time spent in each location. The radiation contributing to external dose was primarily beta and photon (including X-rays) and neutron.

Beta/Photon Characterization

Beta and photon radiations are well-characterized in ORAUT-TKBS-0006-6. Beta radiations were measured along with photon radiation by the Hanford personnel dosimetry and portable instruments. Potential exposure to workers, particularly in reference to skin or extremity dose, was routinely considered. Dose reconstruction for beta radiation, which is typically accompanied by photon radiation in Hanford work areas, is characterized in ORAUT-TKBS-0006-6. The values in Table 7-4 are intended to provide a claimant-favorable estimate of parameters that will be used to calculate the organ dose for long-term Hanford workers.

Table 7-4: Default Beta and Photon Energies/Percentages for Hanford DuPont Operations

Table 7-4 and corresponding notes span two pages.

Area	Operations Starting Date-Operations Ending Date	Radiation Type	Energy Percentages		
			<30 keV	30-250 keV	>250 keV
Fuel Fabrication Facilities (300 Area, Buildings 313, 306, 333)	1945 -1972	Photon[1]	0%	100%	0%
Reactors (100 Area, 105-B, D, F, H, DR, C, KW, KE, and N Reactors, 400 Area FFTF, and 300 Area Test Reactors)	1944 - 1987	Photon[1]	0%	25%	75%
Processing Plants and Radiochemical operations (T, B, S-REDOX, C, A - PUREX, U Plant, UO_3 Plant)	1944 - 1988	Photon[1]	0%	25%	75%
Plutonium Production (including PFP, Z-Plant, 234-5Z, 231-Z, Pu Laboratories 308/309, 324 Plant)	1945 - 2003	Photon	25%	75%	0%
Calibrations	1945 - 2003	Photon[1]	0%	25%	75%
Waste Handling	1945 - 2003	Photon[1]	0%	50%	50%

Notes:
The source of this table is ORAUT-TKBS-0006-6, Appendix A, Table A.2, page 93.
[1]Beta energies in these areas are 100% > 15 keV

Neutron Field Characterization

Hanford workers had the potential to be exposed to neutron radiation during operation of the reactors in the 100, 300, and 400 Areas and during plutonium concentration and finishing work in the 200 and 300 Area Plutonium Facilities.

At the 100 Area nuclear reactor facilities, the 300 Area test reactors, and the 400 Area Fast Flux Test Facility, neutrons were generated by fission of uranium and plutonium in the reactor core. Neutron exposures for workers in the reactors were accompanied by photon radiation that was readily measured with Hanford portable instrumentation and/or dosimetry capabilities. These facilities generally had extensive shielding to reduce worker neutron and photon radiation exposure in most work areas. Neutron radiation was typically significant only while a reactor was in operation and only in those areas of a reactor that were typically restricted to general worker access. Reactor areas were categorized according to hazard potential because there were known areas of potential worker exposure to significant neutron (and photon) beams of radiation, such as those associated with instrument and test penetrations of the single-pass reactors (ORAUT-TKBS-0006-6).

At the 200 Area Plutonium Facilities and the 300 Area plutonium laboratories, neutron radiation was generated from plutonium by either spontaneous fission, or importantly, by alpha-particle interaction with light elements such as oxygen, fluorine, and beryllium. These interactions are commonly referred to as alpha-n reactions. The most significant source, historically, of neutron exposure in the Hanford 200 Area Plutonium Facilities was the Plutonium Fluorination process (PuF_4) (ORAUT-TKBS-0006-6).

Significant mapping of the dose rates, and evaluations of thermal and fast neutron fluxes are available for workplaces in the single pass reactors from 1944 through 1971. Neutron spectra measurements performed in the 1970s have been located in areas such as the Fast Flux Test Facility and the Plutonium Finishing Plant. Results of these studies can be found in ORAUT-TKBS-0006.

7.3.1.2 History of Whole Body External Monitoring

Historically, using portable radiation instruments, zone controls, and personnel dosimeters, Hanford had an extensive radiation safety monitoring program. Results from the personnel dosimeters were used to measure and record dose from external radiation exposure to Hanford workers throughout the history of Hanford operations.

Routine Hanford practices appear to have required assigning dosimeters to all workers who entered a controlled radiation area. A 1948 document by Herbert M. Parker, which reviews the film badge program at the time, states that the incorporation of the film badge into the security badge has proved effective and that all persons entering restricted Plant areas are required to wear the badge at all times (Parker, 1948). This review also states that all construction workers within the boundaries of the 100, 200, and 300 Areas shall wear the film badge at all times (Parker, February 1948).

The trends in the number of workers who were monitored, the number of monitored workers with positive dose, and the collective dose from photon radiation, do not show any abrupt changes that would be indicative of significant changes in photon dosimetry capabilities or assignment of dosimeters (ORAUT-TKBS-0006-6).

The two-element film dosimeter was used from October 1944 to March 1957. This design was also used at the Clinton laboratory (now ORNL) and later by other MED/AEC/DOE laboratories, and was based on the dosimeter design developed at the Metallurgical Laboratory in Chicago, Illinois, by Pardue, Goldstein, and Wollan. The minimum detectable dose based on laboratory irradiations was 0.3 mSv (30 millirem), and the routine dosimeter exchange period was weekly. From 1944 to 1957, Hanford assigned skin dose based on the dosimeter open-window reading plus the silver-filtered dosimeter reading (ORAUT-TKBS-0006-6).

From April 1957 to December 31, 1971, Hanford used multi-element film dosimeters to measure beta, X-ray, and gamma radiation dose components in one of two designs during the periods of 1958 to 1961 and 1962 to 1971, respectively. These "beta/photon" film dosimeters consisted of four shielded areas and provided a substantially improved capability to measure both deep and shallow dose. Processing results (i.e., optical density) were recorded for the film response behind each filter and an algorithm was used to calculate the respective dose components. Beginning in 1958, the dosimeters were calibrated with a plutonium tetrafluoride source in order to better duplicate the neutron energies in Hanford's plutonium facilities. The skin dose of record was calculated as the sum of the whole-body and non-penetrating doses (ORAUT-TKBS-0006-6).

Beginning January 1, 1972, Hanford used thermoluminescent dosimeters (TLDs) in various configurations. A "Basic" TLD, a one-chip design with limited capability for beta and photon (X- and gamma ray) radiation, was used from January 1, 1971 through about 1988, and was assigned to personnel considered to have little or no potential to receive dose. The Hanford Multipurpose TLD was used from January 1, 1972 to December 1994 to measure beta, photon, and neutron radiation. These dosimeters were assigned to personnel likely to work in radiation fields. Hanford Multipurpose TLDs originally had a five-chip design, which was changed to a four-chip design in July 1977 to enable the use of a commercial reader system; then, in January 1983, the Hanford Multipurpose TLDs returned to a five-chip design until the system was replaced on January 1, 1995 with a commercial system. The same filtration was used in Hanford Multipurpose TLDs during all years of use. The Hanford Multipurpose TLD was first accredited for performance testing in 1989 by the DOE Laboratory Accreditation Program in beta, photon, and neutron radiation categories (ORAUT-TKBS-0006-6).

7.3.1.3 History of Extremity Monitoring

Indications of an extremity dosimetry program exist as early as 1944 and 1945, with finger-ring dosimeters being referred to in weekly Health Instrument Section reports (Parker, 1945). Parker mentions the use of film and micro-ionization chambers for extremity monitoring in a 1948 paper (Parker, 1960). Early extremity dosimeter rings consisted of an aluminum ring holding a disc of film which responded to beta and photon radiation without any capability to distinguish between the two components. A silver disc shield was later added to allow a limited capability for distinguishing the gamma component. Finger-ring dosimeters could be bulky and sometimes could not be used in tight areas. In such cases, a pliable film packet was used (Parker, no date).

Starting in mid-1967, a flexible rubber finger ring, which utilized a wafer of ^{7}LiF-impregnated Teflon, was available for routine hand dosimetry. This dosimeter had a wide range of response that provided more than adequate coverage for all work situations, as well a minimal energy dependence allowing its use for essentially any photon energy from plutonium to cobalt-60 photons (Wilson, 1987).

In 1974, a plastic ring, designed by the U.S. Testing Company, containing a single TLD-700 chip, was used for hand monitoring (Fix, 1981).

A wrist dosimeter, similar to a wristwatch, has also been used extensively in locations where exposure to the hands and forearms may be the limiting factor. In addition, flexible dosimeters with appropriate shielding materials were used extensively by underwater divers when repairing storage basins. These dosimeters could be affixed to almost any part of the body to determine the limiting exposure location where the source material could not be shielded or known with any certainty in remote locations of the basin. These dosimeters have also been used in work locations where the head and/or eyes may be the limiting exposure organ of the body (Wilson, 1990).

Records indicate that between the years of 1946 and 1989, an average of 530 workers each year had extremity dosimetry results (with a high in 1963 of 1596 workers and a low in 1948 of 263 workers) (Buschbom, 1993). The dose records received by NIOSH from DOE for Energy Employee claimants include provisions for extremity dose results, which for some employees, contain extensive data.

7.3.1.4 History of Neutron Monitoring

With possibly one exception described below, the historical record shows that Hanford assigned neutron dosimeters to employees with any significant potential for exposure to neutron radiation. Hanford has used three general types of neutron dosimeters, which differ substantially in their responses to neutron radiation.

Hanford implemented neutron dosimetry in 1944 by using enriched boron-lined pocket ionization chambers. The boron liners were sensitive only to thermal neutron exposure, (Wilson, 1987; Fix, February 1997). Some attempts were made during this time to measure fast neutrons using a fine-grain film to record tracks from recoil protons, but these attempts were unsuccessful (Wilson, 1990).

Starting on January 1, 1950, the Eastman-Kodak Nuclear Track Emulsion Type A (NTA) film dosimeter was implemented. Indications are that the weekly-exchanged Hanford NTA film was generally processed independently from the bi-weekly exchanged beta/photon dosimeter. Prior to 1957, NTA film was housed in the two-element beta/photon dosimeter holder along with the beta/photon film. Beginning in 1958, the NTA film was housed in a Hanford Neutron Dosimeter along with a beta/photon film. There was space available in the yearly forms (manually prepared before 1957) to record the neutron dose. The Hanford policy to process NTA film varied historically, but generally involved the practice of reading all NTA film for the 200 Area West Plutonium Facilities and, for other Hanford facilities, processing the NTA only if the photon dose was at least 100 mrem. This policy was based on the observation that neutron dose was always accompanied by photon dose (Watson, 1959). For the other facilities, potential neutron dose was considered to be relatively small compared to photon dose. A neutron dose is recorded for all Hanford workers assigned an NTA film. If it was not processed, a zero neutron dose was recorded. The earliest recorded neutron dose for Hanford workers dates from 1950 (ORAUT-TKBS-0006-6).

Starting January 1, 1972 through present day, TLDs have been used to measure neutron doses. As outlined in ORAUT-TKBS-0006-6, several configurations were used:

Five-Chip Hanford Multipurpose TLD, January 1972 to June 1977—The five-chip Hanford Multipurpose TLD incorporated a neutron dose capability that involved three of the five chips (i.e., 3, 4, and 5). The combination of these chips allowed estimation of thermal (i.e., slow) and fast neutron components with the capability (chip 5) for an accurate beta/photon response correction (i.e., neutron-sensitive chips also respond to photon and high-energy beta radiation). Effective July 1, 1977, the dose algorithm was changed to use data for only four of the chips (i.e., omitting chip 5) to utilize the four-chip cards that were being implemented (ORAUT-TKBS-0006-6, page 18-19).

Four-Chip Hanford Multipurpose TLD, July 1977 to December 1983—The Hanford Multipurpose TLD dosimeter was modified to a four-chip design to accommodate introduction of a commercial reader system in the later 1970s that required the dosimeter cards to pivot around the center where chip 5 was located. Tens of thousands of Hanford Multipurpose TLD cards were fabricated with chip 5 removed. These modified cards were used in the original five-chip holders (ORAUT-TKBS-0006-6, page 19).

Five-Chip Hanford Multipurpose TLD, January 1984 to December 1994—Routine dose evaluation using the five-chip Hanford Multipurpose TLD began again on January 1, 1984. Several refinements were made to this system (Wilson, 1990) to prepare for DOE Laboratory Accreditation Program performance testing. The Hanford Multipurpose TLD was first accredited by the DOE Laboratory Accreditation Program for performance testing in neutron categories in 1989, and reaccredited every subsequent (typically 2-year) accreditation cycle thereafter (ORAUT-TKBS-0006-6, page 19).

7.3.1.5 Dosimetry Records

From essentially the beginning of operations, a centralized radiological records program was established at Hanford. Records of radiation doses to individual workers from personnel dosimeters worn by workers are available for Hanford operations beginning in 1944 (Buschbom, 1993). External dosimetry data and related records are readily available for the Hanford operational period from September 1, 1946 through December 31, 1990. The current radiation exposure database is REX, maintained by the Hanford Radiation Records Program. Other repositories of Hanford dosimetry records include the SRDB, NOCTS, and CEDR.

7.3.1.6 Application of Co-Worker Data for External Dose Reconstruction

For unmonitored workers, co-worker doses from monitored workers are presented in *External Coworker Dosimetry Data for the Hanford Site*, ORAUT-OTIB-0030 for photon radiation. Co-worker doses for non-penetrating radiation doses could readily be prepared if needed. Co-worker data may be used for cases not having complete monitoring data and may fall into one of several categories including:

- The worker was unmonitored and, even by today's standards, did not need to be monitored (e.g., a non-radiological worker)
- The worker was unmonitored, but by today's standards would have been monitored
- The worker may have been monitored, but the data are not available to the dose reconstructor

- The worker has partial information, but it is insufficient to complete the dose reconstruction

The Hanford Co-worker study was developed using dosimetry data for monitored Hanford workers from the CEDR database maintained by DOE. The CEDR data represent calculated annual penetrating dosimetry data provided by the Hanford site, which correspond to the shielded dosimetry readings and exclude neutron doses (ORAUT-OTIB-0030).

7.3.2 Ambient Environmental External Radiation Doses at Hanford

ORAUT-TKBS-0006-4 and ORAUT-PROC-0060 provide the rationale, historical background, and data for the reconstruction of occupational environmental doses for unmonitored personnel at the Hanford site. The occupational environmental dose is the dose received by individuals while outside operational facilities such as process buildings, Chemical Separations Plants, reactors, or other structures. External dose from radioactive materials outside the body may be determined from immersion in a cloud of inert gases; deposition of particles on the skin; or adjacent operational facilities.

7.3.2.1 Ambient Radiation

Table 4.8 of ORAUT-TKBS-0006-4 lists the external gamma measurements at Hanford from 1944 through 2001, including fallout and background. The values are given in averages in millirem per year for exposures of 2,000 hours/year, and can be used to reconstruct dose from environmental radiation sources.

7.3.2.2 Skin Deposition of Airborne Particulate Emissions

Starting in 1947, surveys of the T and B Plant area grounds revealed contamination in the form of discrete particles. The most likely source of these particles was iron-oxide particulates coated with radioactive material from corroding ductwork in the T and B Plant ventilation systems. Analysis of the particles indicated that the radionuclides were deposited on the blowers and other iron surfaces and were released into the ventilation air stream as the iron parts corroded. Although the particles were not discovered until 1947, these releases could have been ongoing from the start of operations. These particles were emitted through April 1948, when sand filters were installed to stop the releases. The greatest activity measured on a T or B Plant particle was 3.2 µCi, with the average being 1.1 µCi. ORAUT-TKBS-0006-4, Section 4.3.3, provides a method to estimate dose based on a conservative particle activity, the probability that a particle could land on a worker's skin, mean residence times, and dose coefficients for different radionuclides on the particles (ORAUT-TKBS-0006-4).

7.3.2.3 Release of Noble Gases

Xenon-133 was released from the production reactors and its dose contribution can be estimated by comparing it with the iodine-131 release rate and dose conversion factors. At its peak in 1945, when Hanford used shorter fuel-element cooling times, the xenon-133 release rate was 42,000 Ci/mo. The iodine-131 release during the peak time was 89,000 Ci/mo. When comparing the dose conversion factors and release rates of iodine-131 and xenon-133, the iodine contribution to the dose was more

than 10,000 times larger than that of xenon. Therefore, iodine is listed as a major contributor and xenon-133 is not (ORAUT-TKBS-0006-4).

Argon-41 was released from the Hanford reactors as a neutron activation product of stable argon in air, but not from the Chemical Separations Facilities. Effluent concentrations were measured sporadically for only brief periods, and the reactors did not operate continuously. Table 4A-11 in ORAUT-TKBS-0006-4 provides submersion gamma dose and skin dose values that can be used to reconstruct dose.

7.3.3 Hanford Occupational X-Ray Examinations

Pre-employment, termination, and periodic medical examinations were given to Hanford workers from the very beginning of site operations. Cantril gives a count of 15 exams being given in December 1943, and states that the periodic exam program began in January 1944 (Cantril, 1946). These examinations were performed for the purpose of evaluating biological indicators of radiation exposure (i.e. blood cell counts) and included a chest X-ray.

In the site's early years, periodic X-ray examinations were relatively frequent. Groups of workers identified as being at-risk received medical exams, including X-rays, at more frequent intervals than other workers. For work with radiation hazards, interval exams in January 1944 were as close to every four weeks as possible. By July 1945, the exam intervals were lengthened from every four to every seven or eight weeks. Other employees not working with radiation or other special hazards were examined every three to six months. As experience was gained with the outcome of these examinations, the frequency of medical radiographs was reduced to an annual occurrence until 1959, and thereafter, on a schedule dependent on age, but no more frequent than annually (ORAUT-TKBS-0006-3).

A review of the available documentation of the Occupational Medical program at Hanford from 1943 to the present revealed that only three diagnostic medical radiographic procedures were administered in connection with pre-employment or regular post-employment medical examinations, these included (1) a posterior-anterior 14"×17" chest film, (2) a lateral 14"x17" chest film, and (3) a photofluorographic 4"×5" chest film.

The 14"×17" posterior-anterior chest radiography was the most widely used diagnostic procedure. In some cases, stereo views were taken; these required two 14"x17" films.

Beginning in March 1945, when Hanford received fluoroscopic equipment, photofluorographic chest films were taken. This method resulted in much greater worker doses than a standard radiographic procedure. Photofluorography used a smaller film (typically 4"×5"), a smaller source-to-skin distance, and typically resulted in a several-fold greater radiation exposure. Exposure was regulated by photometers, which used exposure to the film to determine the time of exposure (Cantril, 1946; ORAUT-TKBS-0006-3).

7.3.4 External Dose Reconstruction

Through August 9, 2007, 2,564 EEOICPA claims from the Hanford workers had been submitted to NIOSH. Of those 2,564 claims, which cover the entire range of operation at the Hanford site, 2.370 claims had external monitoring data provided by DOE.

There is an established protocol for assessing external exposure when performing dose reconstructions (these protocol steps are discussed in the following subsections):

- Photon and Electron Dose
- Neutron Dose
- Unmonitored Individuals Working in Production Areas
- Medical X-ray

7.3.4.1 Photon and Electron Dose

External dose has been measured and recorded for Hanford personnel since the beginning of site operations. Based on information in the Hanford Site Profile and associated references, the recorded photon penetrating dose to Hanford workers is reasonably accurate for all years and for all facilities. The Hanford dosimetry systems have been extensively evaluated. Importantly, all Hanford workers entering radiological areas were required to wear dosimeters. Additionally, Special Work Permits were used for higher-dosed activities and generally involved workers using two-pocket ionization chambers.

As previously shown in Table 4-1, the majority of completed dose reconstructions have included external dose records provided by DOE. Hanford worker-recorded dose measurements are considered reasonably accurate from 1944 through the present with one exception, that being a potential under-response of the early (pre-1958) two-element dosimeter penetrating dose to low-energy X-rays, such as at the Plutonium Facilities. However, the non-penetrating dose component can be used to compensate, thus allowing a reasonable estimate of the penetrating photon dose. The stated historical Hanford practice (for Plutonium Facilities only) was to add to the penetrating dose, 20% of the measured non-penetrating dose. However, NIOSH has not been able to confirm that this was done for all years. Therefore, if the early photon dose is significant to the dose reconstruction, ORAUT-TKBS-0006-6 recommends that the penetrating dose be adjusted by using 20% of the non-penetrating or shallow recorded dose to ensure a claimant-favorable assigned photon dose (ORAUT-TKBS-0006-6, page 17).

Missed dose, which may occur when the dose of record is zero because the dosimeter response was less than the minimum detection level or there is no dose of record for an assigned badge for a monitoring period, is accounted for by assigning a missed photon dose based on the minimum detection level divided by 2 (MDL/2) and then multiplied by the number of dosimeter exchange periods for the dosimetry system (ORAUT-TKBS-0006-6, pages 50-51).

Hanford began using extremity dosimetry as early as 1945. A standard monitoring practice in Operational Health Physics is to establish a factor between whole-body and extremity exposure radiation safety limits for the purpose of determining when extremity dosimeters should be assigned. Conservatively, it would not be necessary to monitor the extremity dose unless it was greater than three times the whole-body dose. To assign extremity dose for workers who have extremity cancer but no extremity dose data, the measured whole-body dose should be increased by a factor of three as a claimant-favorable assumption (ORAUT-TKBS-0006-6).

An adjustment for glovebox workers is used to adjust the measured photon dose for Hanford workers in Plutonium Facilities, based on the guidance in *Best Estimate External Dose Reconstruction for Glovebox Workers* (OCAS-OTIB-0010).

To account for the uncertainty in routine beta/photon dosimeter measurements, a standard error of +30% is recommended for use in reconstructing the annual dose. This is based on the estimated standard uncertainty of ±30% in individual recorded film badge doses from photons of any energy (ORAUT-TKBS-0006-6).

Based on the information available to NIOSH, the external photon and electron dose for the class under evaluation can be reconstructed with sufficient accuracy.

7.3.4.2 Neutron Dose

As stated before, there are no recorded neutron doses at Hanford prior to 1950 when the Pocket Ionization Chamber (PIC) was the sole neutron monitoring dosimeter. Relatively little neutron dose, compared to the recorded whole-body dose from photon radiation, was recorded prior to 1957. Subsequently, much greater neutron dose was recorded from 1957 to 1972 when the Hanford Multielement beta/gamma and neutron film dosimeter systems were used. Then, with implementation of the Hanford Multipurpose Dosimeter on January 1, 1972, the entire energy spectra was measured thus the doses measured are considered reasonably accurate. In contrast, significant whole-body dose from photon radiation is recorded throughout the history of Hanford operations (Buschbom, 1993; Fix, February 1997).

Nuclear Track Emulsion Type A (NTA) Film—beginning in 1950, with its use continuing through 1971, NTA film was used to monitor neutron exposure at Hanford. NTA film was the industry standard of personnel neutron dosimetry during the 1950s and 1960s.

As noted earlier, a two element neutron dosimeter was used from 1950 to 1958. This two element dosimeter used a silver filter to absorb low energy photons which if not absorbed would darken the film inhibiting the identification of proton-recoil tracks. The major problem with this dosimeter is that it effectively only responded to neutrons with energies greater than 0.450 MeV. This dosimeter was calibrated using a PoBe source which has an average energy of 4 MeV. Thus for exposure to plutonium metal, fission spectra neutrons, and PuF4, this calibration and subsequent evaluation of dosimeters resulted in an under estimate of the actual dose.

Starting in 1958, a multi-element NTA dosimeter was used that included a tin filter and a cadmium filter. Due to the relatively large cross section of the cadmium for thermal neutrons, and the subsequent n,γ reaction, the difference in the optical density between the tin and cadmium filter was

due to thermal neutrons (Wilson, 1990). Thus effectively the new multi-element design extended the energy response of the neutron dosimeter over the two element design. For the new multi-element neutron dosimeter effectively responded to neutrons greater than 0.450 MeV (3 grain track) and to neutrons less than 5e-7 MeV (epithermal to thermal energies). The intermediate energy range (5e-7 MeV to 0.450 MeV) was the only gap in the response of the multi-element NTA dosimeter. The energy response gap however, was effectively accounted for through the calibration methodology. Also starting in 1958, PuF_4 was used for the calibration of the multi-element neutron dosimeter. The PuF4 neutron energy spectra extends from a maximum of around 3 MeV down through the intermediate, epithermal and thermal energies with an average of around 1.3 to 1.4 MeV (Lehman, 1968, Wilson, 1990, and Brackenbush et al., 1991). Thus by calibrating to the primary source of neutron exposure in the 200 area the lack of response in a particular region is effectively corrected for during the calibration. It is also important to note that the actual number of grains used to identify a track becomes less important in that if a 5 grain track was the minimum for track identification, proportionally there would be less 5 grain tracks identified during the calibration for the same dose compared to 3 grain tracks. Thus while the neutron energy response and subsequent calibration factor could vary depending on whether a 3,5, or 7 grain track were used, the relative measured dose did not, because the calibration factor would also change.

The average neutron energy of PuF_4 is lower than the average fission neutron spectra of approximately 2.0 MeV. Due to this energy difference exposure to plutonium metal while using a PuF_4 calibration source would result in a slightly claimant favorable overestimate of the dose. Thus for the remainder of the 200 area facilities, the use of the PuF_4 calibration source and the multi-element neutron dosimeter results in a reasonably accurate dose assessment that tends to be claimant favorable due to the slightly harder neutron energy spectra of plutonium metal compared to PuF_4.

The response of the multi-element NTA dosimeter to a moderated fission spectrum around the graphite reactors was also evaluated. NIOSH has obtained survey reports of thermal, fast and gamma flux measurements at many locations of the graphite reactors which provides sufficient evidence for the evaluation of neutron dose at these facilities.

Several factors make reading the individual tracks for lower energies more difficult: (1) the shorter proton tracks caused by the lower energy neutrons, (2) photon fogging of the film, (3) fading of the film, which occurred during the elapsed time between exposure and processing, and 4) technician fatigue (counting the films day after day, particularly with little or no distinguishable neutron-induced tracks).

However, Hanford did have several processes in place to help mitigate these errors. By using a standard track length for both the calibration and for track identification the issue of shorter tracks was minimized. The fading of the films was minimized by using a two week exchange cycle and by aging the calibration films two weeks to simulate the period of wear by site personnel (Wilson, 1987). To mitigate technician fatigue, Hanford had an extensive training program for the technicians, the individual NTA films were read by multiple technicians thus duplication, the time an individual technician could spend reading films was limited to four hours, and control and exposed films were included as blind audits to check on the accuracy of the technicians reading the films.

Hanford Multipurpose TLD—Hanford improved neutron measurement capabilities by implementing the use of the Hanford Multipurpose TLD on January 1, 1972. Since 1972 dose

measurements are considered reasonably accurate with the exception of a period from 1978 through 1983 when a 4-chip Hanford TLD was used. The recorded neutron dose during this period was too low. A study conducted at that time showed an average under-recorded neutron dose of about 35% (Fix, February 1997). Thus, ORAUT-TKBS-0006-6 recommends that a factor of 1.35 times the recorded neutron dose be used when performing dose reconstructions to ensure a claimant-favorable assigned neutron dose.

To account for the uncertainty in the neutron Hanford Multipurpose TLD dosimeter measurements, starting in 1972 a standard error of +50%, based on actual DOE Laboratory Accreditation Program performance testing, is recommended by ORAUT-TKBS-0006-6 for use in reconstructing annual dose.

Use of Neutron-Photon Ratios to Reconstruct Neutron Dose—
As stated above, neutron doses determined prior to 1958 with the two-element NTA film dosimeter and the PIC are likely too low due to the dosimeter design and the calibration methodology. Since it is unlikely that a significant neutron dose would not be accompanied by a gamma dose, using a claimant-favorable neutron-to-photon ratio distribution can be used to estimate an upper bound to the worker neutron dose during the time prior to the use of the Hanford multi-element neutron dosimeter in 1958.

For the single-pass reactor area dose reconstruction, the measured photon radiation dose for Hanford workers is reasonably accurate for all years of single-pass reactor operation. Hanford employees entering a radiological controlled area were required to wear a personnel film dosimeter, and typically, a pair of pocket ionization chambers (PICs). Significant differences in measured dose between the film dosimeter and the PIC would have been a topic of investigation (Smith, 1947), as is noted in the dosimeter monitoring procedures and in routine monthly reports. Hanford had established protocols for classifying reactor workplaces according to potential danger and Special Work Permits were required for workers to access these areas (HAPO, 1949-1950; HAPO 1947-1950). Documents by Wilson (1987), Wilson (1990), and Fix (February 1997) describe the potential level of neutron dose received from Hanford single-pass reactors as being less than 5%, approximately, of the photon dose. NIOSH has recently obtained and examined Hanford Engineer Works Monthly Reports beginning in 1944 that document shielded and unshielded gamma and neutron dose rate and flux surveys performed in various reactor areas. Survey locations included the reactor faces, experimental test penetrations, and operations and maintenance work locations. The surveys were performed under various single-pass reactor operating conditions and configurations.

For example, a 1945 report provides the combined (photon, beta, slow neutrons, and fast neutrons) dose rate on the face of the three reactors in operation at that time. Figure XX depicts isodose curves for the B, D, F reactors in July 1945. While these data provide details which may warrant revision of the existing neutron to photon dose ratios currently used in the Hanford Technical Basis Document, it is also important to note that the maximum combined radiation dose rate measured in this survey of the face of the B reactor was 7 mrem/hr. Assuming continuous exposure, 2000 hours per year on the platform at that location, at this rate would result in a combined (photon, slow neutron, and fast neutron) upper bound dose of 14 rem.

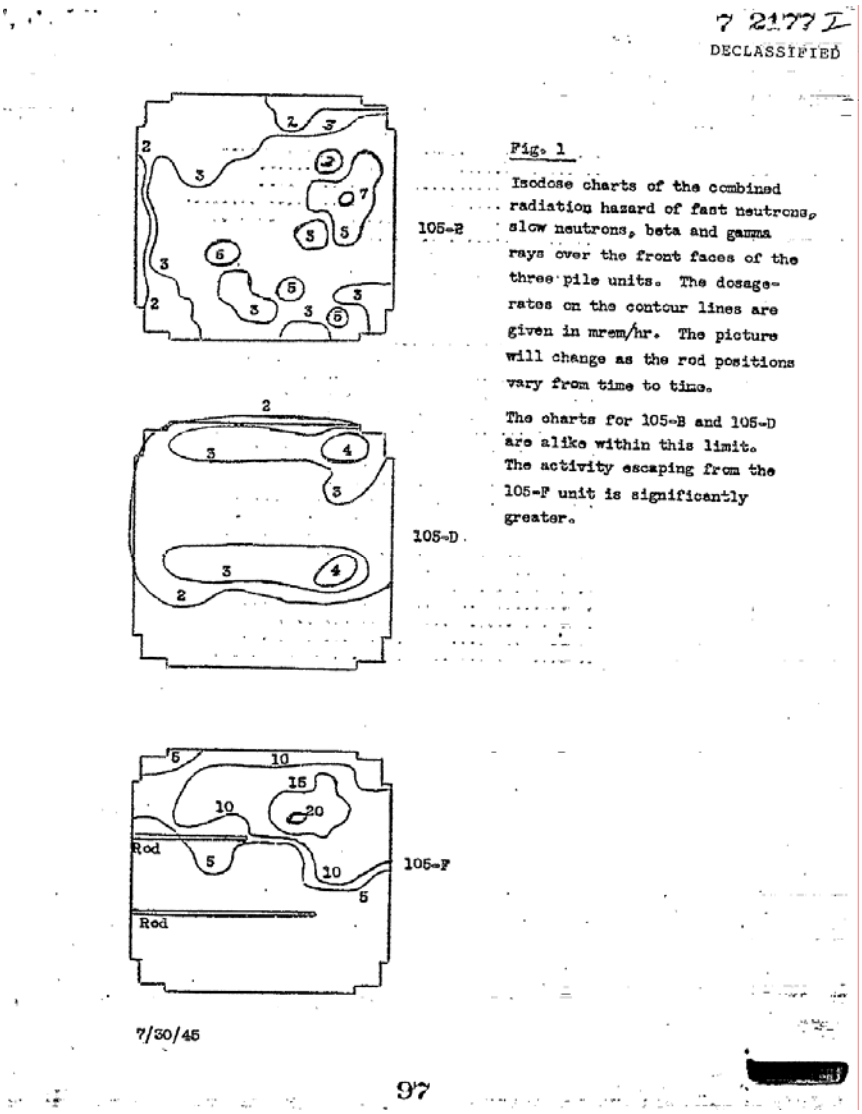


Figure 7-1: Example of isodose curves found in Hanford Monthly Reports

An excerpt from a June 1945 report (HW-2177, Hanford Engineer Works Monthly report, July 1945) indicates that for the top of the reactor, the dose rates were considerably higher at 45 mrem/hr, and that the gamma, fast and thermal neutrons were fairly equally divided at approximately 15 mrem/hr each.

The available data are sufficient to validate or revise the neutron to photon ratios currently used for dose reconstruction. The ratios are applied in the determination of missed neutron dose (i.e., multiplying the potential missed photon dose by a neutron-to-photon dose ratio) and in assigning a neutron dose based on the measured photon dose.

For neutron exposures to workers at the N Reactor, which operated from 1963 through 1987 in the Hanford 100 N Area, the Hanford Multipurpose TLD paired neutron and photon data are available from 1972 through 1987. As such, the neutron-to-photon ratio measured with the Hanford Multipurpose TLD for the period of 1972 through 1987 is likely to closely resemble the ratio from 1963 through 1971, unless a major facility design change occurred. During interviews with former

health physicists with a history of working at the N-Reactor throughout all the years of its operation, it was stated that there was no reason for the ratio to significantly change (Personal Communication, 2007).

For dose reconstruction workers in the Plutonium Facility, the measured photon radiation dose is reasonably accurate for all years of operation using a combination of non-penetrating and penetrating dose components from the Hanford film dosimeter results, as described in Parker (February 1948), Wilson (1987), and in ORAUT-TKBS-0006-6. ORAUT-TKBS-0006-6 recommends using a distribution of neutron to photon dose ratios to assign neutron dose to Hanford plutonium workers. The distribution is based on paired photon and neutron dose measurements with the Hanford Multipurpose TLD. These distribution parameters are consistent with the AEC 1972 Investigation of Hanford worker neutron doses, which used maximum neutron to photon dose ratios (Wilson, 1972) to retrospectively evaluate the Hanford career whole-body dose for selected workers (Biles, 1972). The neutron to photon dose ratio is applied in the determination of missed neutron dose (i.e., multiplying the potential missed photon dose by a neutron to photon dose ratio) and in assigning a neutron dose based on the measured photon dose. Field measurements, including extremity, neutron, and photon dose components have often been performed at the Hanford plutonium facilities (Roesch, August 1951; Roesch, July 1954; Roesch, July 1957; Reddie, 1949; Glasgow, 1951; Brown, October 1958; Brown, November 1958; Helgeson, November 1956; Helgeson, November 3, 1955; Helgeson, December 15, 1955; Helgeson, February 20, 1956; Helgeson, May 23, 1956; Helgeson, September 8, 1956; Helgeson, August 9, 1956; Helgeson, August 31, 1956; Helgeson, October 2, 1956; Helgeson, October 12, 1956; Helgeson, October 15, 1956; Helgeson, October 31, 1956; Helgeson, November 1, 1956; Helgeson, November 5, 1956; Helgeson, November 9, 1956; Helgeson, November 12, 1956; Helgeson, November 20, 1956; Helgeson, November 27, 1956; Moulthrop, September 21, 1949; Moulthrop, October 9, 1957; Moulthrop, March 20, 1958; Moulthrop, March 27, 1958; Moulthrop, May 21, 1958; Moulthrop, September 5, 1958; Moulthrop, October 22, 1959—Part 1; Moulthrop, October 22, 1959—Part 2; FEFPTP, 1960).

For other areas where there is significant potential for neutron dose, such as the 300 Area Test reactors and Laboratory facilities, guidance is given to dose reconstructors to evaluate the area according to the two methods of neutron exposure (i.e., reactor or plutonium) that most closely fit the exposure pattern (ORAUT-TKBS-0006-6).

Other methods to validate the neutron to photon dose ratios described in the Hanford technical basis documents are being developed and evaluated by NIOSH. For example, NIOSH is modeling the neutron and gamma ray fluxes from selected gloveboxes in the Plutonium Finishing Plant (the Plutonium Fluorination gloveboxes) using the ATILLA radiation transport code. The ATILLA code was developed at the Los Alamos National Laboratory as a tool to predict how neutron radiation travels through space and materials, using a deterministic approach. NIOSH also has the 1950 through 1961 Hanford NTA processing data, which provides another option to validate the claimant favorability of the neutron dose calculated using the neutron-photon ratio and the measured photon dose. The 1950 through 1961 NTA data include pre- and post-NTA calibration with the plutonium tetrafluoride source (~1958) that likely has neutron spectra most similar to the neutron spectra in Hanford plutonium facilities, particularly the comparatively high neutron exposure for the fluorination step. In addition, the earlier doses determined with NTA film, once corrected for energy response limitations (i.e., the fraction of the neutron spectra that was not measured by the NTA), can be used as another method of validation.

Missed Neutron Dose—there is a potential for missed neutron dose for Hanford workers. Missed neutron dose for Hanford workers would occur where there is no recorded dose (even though a dosimeter is assigned) or where a zero dose is recorded for any response less than the site dose recording threshold. Estimates of missed neutron dose are determined for the period prior to 1972 by using a neutron to photon dose ratio times the estimated missed photon dose; starting in 1972, estimates of the missed neutron dose for the Hanford Multipurpose TLD dosimeter are based on the respective dosimeter exchange periods multiplied by the MDL/2 (minimum detection level divided by two). This process equates to an annual neutron missed dose of 1,300 millirem for the early boron-lined PIC, 2,100 mrem for the weekly exchanged NTA film, and 300 millirem (assuming a monthly exchange frequency and a minimum detection level of 50 millirem) with the Hanford Multipurpose TLD (ORAUT-TKBS-0006-6).

Neutron Dose Feasibility Conclusion—for neutron exposures after implementation of the Hanford Multipurpose TLD on January 1, 1972, recorded external dosimetry data are extensive and sufficient for external dose reconstruction. For neutron exposures prior to January 1, 1972 but after 1958, Hanford multi-element NTA dosimeter, the recorded doses can be adjusted in a claimant favorable manner to correct for the potential under response around the reactor facilities. Prior to 1958, a claimant-favorable assignment of neutron dose based on the application of a neutron to photon dose ratio distribution can be used for external neutron dose reconstruction. These ratios can also be applied to workers who were not monitored but who potentially should have been monitored.

7.3.4.3 Unmonitored Individuals Working in Production Areas

Although all significantly-exposed Hanford workers should have been monitored with a recorded dose, unmonitored Hanford workers can be assigned unmeasured photon dose by using the Hanford co-worker doses presented in ORAUT-OTIB-0030.

Based on the information available to NIOSH, the dose to unmonitored workers in the class under evaluation can be reconstructed with sufficient accuracy.

7.3.4.4 Medical X-ray

Medical X-rays were performed on Hanford workers from the very beginning as part of their pre-employment, termination, and periodic medical examinations. Records of X-rays performed on a worker are typically included in the dose records provided by DOE. When records are not available, Table 3-3 of ORAUT-TKBS-0006-3 provides guidelines that are used to determine the number of X-rays. For example, Table 3-3 indicates that for dates prior to July 1, 1945, all employees are assumed to have had an entrance, exit, and every 3-6 months a 14”x17” posterior-anterior chest X-ray. Radiation or special hazard workers are assumed to have had an X-ray every 4 weeks. After July 1, 1945, the radiation and special hazard workers’ periodic interval was increased to 4-8 weeks (ORAUT-TKBS-0006-3, page 12). Organ doses are provided in ORAUT-TKBS-0006-3, Table 3-5, and are based on 1940 X-ray practices and dose factors provided in ICRP 34 (ICRP 34; ORAUT-TKBS-0006-3; ORAUT-PROC-0061).

Beginning in March 1945, Hanford received fluoroscopic equipment and began taking photofluorography chest X-rays at the site. These exams typically have a higher exposure than the

14”x17” posterior-anterior chest X-rays. If uncertain as to the type of X-ray a worker received, the higher exposures due to photofluorography can be assumed for dose reconstruction (ORAUT-TKBS-0006-3, page 19-20).

ORAUT-TKBS-0006-3 provides a combined statistical uncertainty factor of +30% that can be assumed based on uncertainties such as measurement error, time of exposure, distance, and variations of tube current.

Based on the information available to NIOSH, the medical X-ray dose for the class under evaluation can be reconstructed with sufficient accuracy.

7.3.5 External Dose Reconstruction Feasibility Conclusion

NIOSH has established that it has access to sufficient information to either: (1) estimate the maximum external radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the class; or (2) estimate the external radiation doses to members of the class more precisely than a maximum dose estimate.

7.4 Evaluation of Petition Basis for SEC-00057-2

The following subsections evaluate the assertions made on behalf of petition SEC-00057-2 for Hanford.

7.4.1 Evaluation of Major Topics Detailed in Petition SEC-00057 and SEC-00078

The following major topics were detailed in petition SEC-00057 and SEC-00078. Italicized statements are from the petition; the comments that follow are from NIOSH. To avoid unnecessary repetition, issues covering similar topics and eliciting similar NIOSH responses have been grouped together.

7.4.1.1 Hanford Workers were Inadequately or Inconsistently Monitored

Similar issues from SEC-00057 and SEC-00078 (OSA Ref ID: 100318, 100105, 100104): *Radiation overexposures and radiation doses potentially incurred by members of all classes at the Hanford Nuclear Reservation were not monitored or consistently monitored through individual monitoring or area monitoring.*

It is evident from available personnel records and monitoring data that not all Hanford employees were monitored at all times. Some workers, who appear to have held jobs that were administrative or managerial in nature and unlikely to result in contact with radiation or radioactive material, may have not been monitored at all. Other workers were clearly monitored on an as-needed basis as determined by the Hanford Personnel Dosimetry Program; still, other workers were monitored constantly if their jobs involved consistent exposure potential. Because a large amount of monitoring data exist for Hanford employees, particularly for those employees working in jobs with highest exposure potentials, gaps in monitoring records for specific employees can be filled by conservatively utilizing available co-worker data. The data and appropriate claimant-favorable techniques for its use in dose reconstruction are primarily contained in *Internal Dosimetry Coworker Data for the Hanford Site* (ORAUT-OTIB-0039) and *External Dosimetry Coworker Data for the Hanford Site* (ORAUT-OTIB-0030).

7.4.1.2 Hanford Construction Workers Were Not Monitored for Internal Doses

Similar issues from SEC-0057 and SEC-0078 (OSA Ref ID: 100105, 100104, 100108): *Petitioners noted a lack of internal monitoring for construction trade workers between 1967 and 1971; construction workers exposed to outside air releases without respiratory protection; and construction workers working in the Tank Farm area with limited access to properly functioning respirators.*

As mentioned in 7.4.1.1 above, a review of available personnel records and monitoring data indicates that not all Hanford employees were monitored at all times. Review of several individual dose reconstructions associated with construction trade workers employed from 1967 through 1971 further indicated a lack of monitoring data for some workers. Internal monitoring data gaps can be covered through the use of conservative assumptions and co-worker data as outlined in ORAUT-OTIB-0039. The proper application of ORAUT-OTIB-0039, specific for performing dose reconstruction for unmonitored construction trade workers, has been further assessed and is detailed in *Parameters to Consider When Processing Claims for Construction Trade Workers* (ORAUT-OTIB-0052). Additionally, guidance contained within *Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses* (ORAUT-OTIB-0054) is available. This guidance can be applied to situations when radionuclide-specific information is lacking, to intakes of fission and activation products associated with most reactor operations, to destructive fuel examination, fuel dissolution, and to high-level waste management operations such as the Tank Farms. Regarding to respirator protection, NIOSH does not take protection factors into account when assessing personnel dose under this radiological dose reconstruction program. That is, assumptions applied in performing EEOICPA dose reconstruction do not include any adjustment or correction to personnel exposures or dose to account for any personal protective equipment that may have been worn (including respirators). This eliminates the need to consider or account for the subsequent performance, or failure, of personal protective equipment for EEOICPA dose reconstructions.

7.4.1.3 Under-recording of Neutron Dose

SEC-00057 (OSA Ref ID: 100318): *Neutron dose was under-recorded for plutonium workers during the period of 1950 through 1971 when the Hanford Nuclear Track Emulsion, Type A, (NTA) film was used.*

As discussed previously in Section 7.4.3.2, the neutron dosimetry systems prior to the implementation of the Hanford Multipurpose Dosimeter (January 1, 1972) had technological inadequacies in accurately measuring neutron dose in the thermal and intermediate spectra. This technical inadequacy is well-documented. For neutron exposures prior to January 1, 1972, NIOSH finds that a claimant-favorable assignment of neutron dose based on the application of a neutron-to-photon dose ratio distribution, supported by Hanford field measurements, can be used for external neutron dose reconstruction.

7.5 Summary of Feasibility Findings for Petition SEC-00057-2

This report evaluates the feasibility for completing dose reconstructions for employees at Hanford from September 1, 1946 through December 31, 1990. NIOSH found that the available monitoring records, process descriptions and source term data available are not sufficient to complete dose reconstructions for the proposed class of employees.

Table 7-5 summarizes the results of the feasibility findings at Hanford for each exposure source during the time period September 1, 1946 through December 31, 1990.

Table 7-5: Summary of Feasibility Findings for SEC-00057-2
September 1, 1946 through December 31, 1990

Source of Exposure	Reconstruction Feasible	Reconstruction Not Feasible
Internal[1]		
- Uranium	X	
- Plutonium	X	
- Fission Products	X	
- Thorium[2]		X
- Tritium	X	
- Polonium	X	
- Americium[3]		X
- Iodine	X	
- Ambient Environmental	X	
External		
- Gamma	X	
- Beta	X	
- Neutron	X	
- Occupational Medical X-ray	X	
- Ambient Environmental	X	

Notes:
[1]Includes an evaluation of urinalysis (*in vitro*), airborne dust, and lung (*in vivo*) data
[2]Considered feasible beginning January 1, 1960
[3]Considered feasible beginning January 1, 1968

As of August 9, 2007, a total of 2,564 claims have been submitted to NIOSH for individuals who worked at Hanford between September 1, 1946 and December 31, 1990. Dose reconstructions have been completed for 1,827 individuals (~71%).

8.0 Evaluation of Health Endangerment for Petition SEC-00057-2

The health endangerment determination for the class of employees covered by this evaluation report is governed by both EEOICPA and 42 C.F.R. § 83.13(c)(3). Under these requirements, if it is not feasible to estimate with sufficient accuracy radiation doses for members of the class, NIOSH must also determine that there is a reasonable likelihood that such radiation doses may have endangered the health of members of the class. Section 83.13 requires NIOSH to assume that any duration of unprotected exposure may have endangered the health of members of a class when it has been established that the class may have been exposed to radiation during a discrete incident likely to have involved levels of exposure similarly high to those occurring during nuclear criticality incidents. If the occurrence of such an exceptionally high-level exposure has not been established, then NIOSH is required to specify that health was endangered for those workers who were employed for a number of work days aggregating at least 250 work days within the parameters established for the class or in combination with work days within the parameters established for one or more other classes of employees in the SEC.

For internal thorium and americium exposures, due to a lack of information regarding internal radiation monitoring, prior to 1960 for thorium, and prior to 1968 for americium, NIOSH's evaluation determined that it is not feasible to estimate radiation dose for members of the proposed class with sufficient accuracy based on the sum of information available from available resources.

9.0 NIOSH-Proposed Class for Petition SEC-00057-2

Based on its research, NIOSH has defined a single class of employees for which NIOSH cannot estimate radiation doses with sufficient accuracy. The NIOSH-proposed class for which NIOSH cannot estimate radiation doses with sufficient accuracy includes:

All employees of the Department of Energy (DOE), its predecessor agencies, and DOE contractors or subcontractors, who were monitored, or should have been monitored for:

1. internal thorium radiological exposures from September 1, 1946 through December 31, 1959 in the following 300 Area facilities: the Metal Fabrication Building (313), the Reactor Fuel Manufacturing Pilot Plant (306), the 300 Area Maintenance Shops (3722), and the Radiochemistry Laboratory (3706); or
2. internal americium radiological exposures from January 1, 1949 through December 31, 1968 in the following areas: the Isolation Building (231-Z), the Waste Treatment Facility (242-Z), and the Plutonium Finishing Plant (234-5Z),

while working at the Hanford Nuclear Reservation for a number of work days aggregating at least 250 work days, or in combination with work days within the parameters established for one or more other classes of employees in the SEC (excluding aggregate work day requirements).

NIOSH has carefully reviewed all material sent in by the petitioner, including the specific assertions stated in the petition, and has responded herein (see Section 7.4). NIOSH has also reviewed available technical resources and other references, including the Site Research Database (SRDB), for information relevant to SEC-00057-2. In addition, NIOSH reviewed its NOCTS dose reconstruction database to identify EEOICPA-related dose reconstructions that might provide information relevant to the petition evaluation.

These actions are based on existing, approved NIOSH processes used in dose reconstruction for claims under EEOICPA. NIOSH's guiding principle in conducting these dose reconstructions is to ensure that the assumptions used are fair, consistent, and well-grounded in the best available science. Simultaneously, uncertainties in the science and data must be handled to the advantage, rather than to the detriment, of the petitioners. When adequate personal dose monitoring information is not available, or is very limited, NIOSH may use the highest reasonably possible radiation dose, based on reliable science, documented experience, and relevant data to determine the feasibility of reconstructing the dose of an SEC petition class. NIOSH contends that it has complied with these standards of performance in determining that it would not be feasible to reconstruct the dose for the class proposed in this petition.

10.0 References

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42 C.F.R. pt. 83, *Procedures for Designating Classes of Employees as Members of the Special Exposure Cohort Under the Energy Employees Occupational Illness Compensation Program Act of 2000*; Final Rule; May 28, 2004; SRDB Ref ID: 22001

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Attachment One—Summary of Internal Monitoring Records in REX, 1946-1992

Table A-1: Summary of Internal Monitoring Records in REX, 1946-1992

(Americium through Cesium-134)

Table A-1 and corresponding notes span two pages.

Year	Americium[1]	Americium-241	Isotopic Americium[2]	Antimony-124	Antimony-125	Barium-140	Berkelium-249	Californium-249	Carbon-14	Cerium-141	Cerium-144	Cesium-134
1946												
1947												
1948												
1949												
1950												
1951												
1952												
1953												
1954												
1955												
1956												
1957												
1958												
1959												
1960												
1961												
1962												
1963												
1964		41										
1965									2			
1966									2		5	
1967		168							24			
1968		114							15			
1969		50							8			
1970		15										
1971		26									84	

Table A-1: Summary of Internal Monitoring Records in REX, 1946-1992

(Americium through Cesium-134)

Table A-1 and corresponding notes span two pages.

Year	Americium[1]	Americium-241	Isotopic Americium[2]	Antimony-124	Antimony-125	Barium-140	Berkelium-249	Californium-249	Carbon-14	Cerium-141	Cerium-144	Cesium-134
1972		62									4	
1973		101									4	
1974		75					4	4		1	6	
1975		48										
1976		793							2			
1977	196	83										
1978		111										
1979	1	132									2	
1980		310										
1981	4	70									2	
1982	13	135				2			3	9	10	
1983	21	38	3	2	1					2	1	
1984		98	10		1						1	
1985		180									2	
1986		183			1				32		1	86
1987		100							1			
1988		41										
1989		28										
1990		26							1			
1991		27										
1992		29										

Table A-1 Notes:

Empty cells indicate no results.

[1]The data code associated with these results was "AM;" this code is assumed to denote americium; Atomic weight(s) are not known

[2]Via alpha spectrometry

Table A-2: Summary of Internal Monitoring Records in REX, 1946-1992
(Cesium-137 through Fission Products)

Table A-2 and corresponding notes span two pages.

Year	Cesium-137	Chromium-51	Cobalt-58	Cobalt-60	Curium-242	Curium-244	Isotopic Curium	Europium [1]	Europium-154	Europium-155	Europium-156	Fission Products [2]
1946												
1947												
1948												
1949												
1950												
1951												
1952												
1953												
1954												
1955												
1956												
1957												
1958												5,698
1959												68,422
1960												7,037
1961												5,918
1962												4,422
1963												3,833
1964												57
1965												
1966												
1967												
1968						6						
1969												
1970									9	9		
1971									7	7		
1972	4								6	6		
1973	13							29	47	46	44	
1974		1		1		8		9	3	3	3	

Table A-2: Summary of Internal Monitoring Records in REX, 1946-1992

(Cesium-137 through Fission Products)

Table A-2 and corresponding notes span two pages.

Year	Cesium-137	Chromium-51	Cobalt-58	Cobalt-60	Curium-242	Curium-244	Isotopic Curium	Europium[1]	Europium-154	Europium-155	Europium-156	Fission Products[2]
1975	9					2			1	1	1	
1976	1					2						
1977						3						
1978	3					2			6			
1979	18											
1980	7											
1981	39			52		4			16	10	11	
1982	15	3	8	18								
1983	13	3	4	10		10	2		2	1		
1984	27			1		45	5		1			
1985	2				13	45	9					
1986	13			1	62	62	3		1			
1987					37	37						
1988	1				10	10	3					
1989					1	1	4					
1990					4	4	1					
1991					9	7						
1992					4	4						

Table A-2 Notes:

Empty cells indicate no results.

[1]The data code associated with these results was "EU;" this code is assumed to denote europium; Atomic weight(s) are not known

[2]Excreta scheduling code for a gamma scan with a germanium detector

Table A-3: Summary of Internal Monitoring Records in REX, 1946-1992
(Mixed Fission Products through ISCP)
Table A-3 and corresponding notes span two pages.

Year	Mixed Fission Products	Ge –Li[1]	Gross Alpha	Gross Beta	GS[2]	Iodine-125	Iodine-129	Iodine-131	Iodine-133	Iridium-192	Iron-59	ISCP[3]
1946												
1947												
1948												
1949												
1950												
1951												
1952												
1953												
1954												
1955												
1956												
1957												
1958												
1959												
1960												
1961												
1962												
1963												
1964												
1965												
1966												
1967												
1968												
1969												
1970												
1971												
1972				1	1							
1973					26							

Table A-3: Summary of Internal Monitoring Records in REX, 1946-1992
(Mixed Fission Products through ISCP)
Table A-3 and corresponding notes span two pages.

Year	Mixed Fission Products	Ge –Li[1]	Gross Alpha	Gross Beta	GS[2]	Iodine-125	Iodine-129	Iodine-131	Iodine-133	Iridium-192	Iron-59	ISCP[3]
1974					55						1	
1975					13							
1976												
1977					1							
1978					15							
1979	2				79	5	3					
1980	1	74		41	97	1					1	
1981		39		46	8			2	2		6	
1982	72	19						2			16	
1983		2						2	2		7	
1984			4									
1985												
1986								2		2		2
1987												
1988												
1989												
1990												
1991												
1992												

Table A-3 Notes:
Empty cells indicate no results.
[1]Excreta scheduling code for a gamma scan with a germanium detector.
[2]Excreta scheduling code for a gamma scan with a NaI detector.
[3]Sequential strontium-90, cerium, promethium

Table A-4: Summary of Internal Monitoring Records in REX, 1946-1992

(Isotopic Pu, Am through Neptunium-237)

Table A-4 and corresponding notes span two pages.

Year	Isotopic Pu, Am[1]	Isotopic Pu, Sr[2]	Isotopic Pu, Sr Tot, Am-241[3]	Isotopic U, Pu[4]	ITPAC[5]	Lanthanum-140	Lead-210	Lead-212	Manganese-54	Molybdenum-99	NAI[6]	Neptunium-237
1946												
1947												
1948												
1949												
1950												
1951												
1952												
1953												
1954												
1955												
1956												
1957												
1958												
1959												
1960												
1961												
1962												
1963												
1964												
1965												
1966												
1967												
1968												
1969												
1970							1	1				
1971												
1972												4

Table A-4: Summary of Internal Monitoring Records in REX, 1946-1992

(Isotopic Pu, Am through Neptunium-237)

Table A-4 and corresponding notes span two pages.

Year	Isotopic Pu, Am[1]	Isotopic Pu, Sr[2]	Isotopic Pu, Sr Tot, Am-241[3]	Isotopic U, Pu[4]	ITPAC[5]	Lanthanum-140	Lead-210	Lead-212	Manganese-54	Molybdenum-99	NAI[6]	Neptunium-237
1973												
1974									1			
1975												
1976												
1977												
1978												
1979												
1980											102	
1981									32		33	
1982						5			19		5	
1983						3			8	1		
1984		1							2			
1985	9	19										
1986	10	1156		4	6				1			
1987	9	138		23	5							1
1988	1	209	1	16								
1989		268		27	1							12
1990	5	323		52	2							
1991		58		3								
1992	7	318		22	5							

Table A-4 Notes:

Empty cells indicate no results.

[1]Isotopic plutonium and americium-241

[2]Isotopic plutonium and strontium

[3]Isotopic plutonium, strontium total, and americium-241; "Sr total" means radiostrontium by gross beta

[4]Isotopic uranium, plutonium

[5]Sequential Isotopic plutonium, curium, americium-241

[6]Gamma NaI detector

Table A-5: Summary of Internal Monitoring Records in REX, 1946-1992

(Neptunium-239 through Radium-224)

Table A-5 and corresponding notes span two pages.

Year	Neptunium-239	Niobium-95	Plutonium[1]	Plutonium-238	Plutonium-239[2]	Plutonium-241	Iso Plutonium	Polonium-210	Potassium-40	Promethium-147	QUS[3]	Radium-224
1946			1,284		200							
1947			3,502		469							
1948			4,712		554							
1949			3,985		402							
1950			5,126		540							
1951			5,760		685							
1952			4,567		467							
1953			7,057		658							
1954			8,176		722							
1955			10,873		910							
1956			11,551		891							
1957			12,062		922							
1958			11,693		968							
1959			6,477		382							
1960			6,306		399							
1961			4,604		243							
1962			3,954		258							
1963			4,667		325							
1964			4,697		400							
1965					4,604							
1966					4,468					74		
1967				3	6,853					422		
1968					4,655			220		314		
1969			2,267	12	392			91		55		
1970					2,867					36		
1971			2,051		380	1		1		20		
1972			1,962	3	638			20		16		
1973				9	2,397							

Table A-5: Summary of Internal Monitoring Records in REX, 1946-1992

(Neptunium-239 through Radium-224)

Table A-5 and corresponding notes span two pages.

Year	Neptunium-239	Niobium-95	Plutonium[1]	Plutonium-238	Plutonium-239[2]	Plutonium-241	Iso Plutonium	Polonium-210	Potassium-40	Promethium-147	QUS[3]	Radium-224
1974		1		6	2,318			3				
1975				12	2,565			4		6		
1976					2,464	3		18		23		
1977				5	2,499			23		29		
1978				3	2,412			26		54		
1979				1	1,957			22		25		
1980			11	85	2,371			1	109,313	6		
1981		4	1,794	7	401			1	313	1		
1982		7	2,055		1				161			1
1983	1	5	1,430	407	456		126	12	85			
1984	1		1	1,922	1,928	1	496		7		75	
1985			1	1,937	1,941	1	491		2	3	154	
1986		1	1	1,822	1,822	3	282		13		73	
1987				1,834	1,834		219				54	
1988				2,489	2,489		321		1		90	
1989			2	2,640	2,640	2	446			1	97	
1990				2,433	2,433		607				66	
1991				3,312	3,352		588				141	
1992				3,128	3,127		691				115	

Table A-5 Notes:

Empty cells indicate no results.

[1]Total alpha from plutonium isotopes after separation

[2]Actually plutonium-239 + plutonium-240

[3]"Quick Uranium Soluble"; excreta scheduling code for elemental uranium

Table A-6: Summary of Internal Monitoring Records in REX, 1946-1992
(Radium-226 through Thorium-234)

Table A-6 and corresponding notes span two pages.

Year	Radium-226	Ruthenium-103	Ruthenium-106	Sodium-22	Strontium[1]	Strontium-89	Strontium-90[2]	Sulfur-35	Technetium-99	Thorium	Thorium-232	Thorium-234
1946												
1947												
1948												
1949												
1950												
1951												
1952												
1953												
1954												
1955												
1956												
1957												
1958												
1959												
1960												
1961												
1962												
1963												
1964												
1965							154					
1966							461					
1967							258	37				
1968							172					
1969							22			4		
1970							55			4		
1971							77					
1972	12				3		92					
1973							95					

Table A-6: Summary of Internal Monitoring Records in REX, 1946-1992
(Radium-226 through Thorium-234)

Table A-6 and corresponding notes span two pages.

Year	Radium-226	Ruthenium-103	Ruthenium-106	Sodium-22	Strontium[1]	Strontium-89	Strontium-90[2]	Sulfur-35	Technetium-99	Thorium	Thorium-232	Thorium-234
1974	2	1	1				107					
1975						2	138					
1976						2	42					
1977					7	1	108					
1978						2	623					1
1979						45	1,173			1		
1980					5	73	1,044			7		
1981			2		745	5	637		2	1	2	
1982		8			196	5	607					1
1983		2			23	2	722					
1984			2		13		1,154					
1985					5	5	1,197					
1986			1	1	4	4	1,142		2			
1987							1,204					
1988					1		1,541					
1989					2		1,582					
1990							1,729					
1991							1,816					
1992							1,685					

Table A-6 Notes:
Empty cells indicate no results.
[1]Total radiostrontium by beta counting
[2]Strontium-90 by yttrium ingrowth

Table A-7: Summary of Internal Monitoring Records in REX, 1946-1992

(Tritium through Total Actinides)

Table A-7and corresponding notes span two pages.

Year	Tritium	Elemental Uranium	Natural Uranium	Uranium-233	Uranium-234	Uranium-235	Uranium-238	Zinc-65	Zirconium-95	Total Actinides
1946		2								
1947		114								
1948		1,019	9							
1949		1,221	9							
1950		960								
1951		1,781								
1952		2,503								
1953		2,434	1							
1954		2,443								
1955		3,959	12							
1956		3,526								
1957		3,326	19							
1958		2,671	152							
1959		2,556	144							
1960		2,860	157							
1961		2,458	122							
1962		1,763	21							
1963		1,791	25							
1964		1,920	26							
1965		2,608	195							
1966		2,237	137							
1967		2,092	97							
1968		1,655	82							
1969		780	104	1						
1970			609	16						
1971		161	17	1						
1972		155	34							
1973			65							

Table A-7: Summary of Internal Monitoring Records in REX, 1946-1992

(Tritium through Total Actinides)

Table A-7and corresponding notes span two pages.

Year	Tritium	Elemental Uranium	Natural Uranium	Uranium-233	Uranium-234	Uranium-235	Uranium-238	Zinc-65	Zirconium-95	Total Actinides
1974			218						1	1
1975		38	259							1
1976		154								5
1977		203								2
1978		362								11
1979		303				1				23
1980		274								88
1981		367						5		65
1982	35	330							10	63
1983	79	199							2	54
1984	562	1,096							1	
1985	175	1,115		15		16	14			
1986	142	951		9	1	10	10		1	
1987	52	961		1		1	1			
1988	42	718		3		3	3			
1989	214	775		4		4	4			
1990	348	812			77	77	77			
1991	1,212	1,663		1	145	146	146			
1992	1,818	2,373		126		126	126			

Table A-7 Notes:
Empty cells indicate no results.