DOE Review Release 09/20/2016

ORAUT-TKBS-0027 Rev. 02
Effective Date: 09/12/2016
Supersedes: ORAUT-TKBS-0027-1 Rev 01, ORAUT-TKBS-0027-2 Rev 01, ORAUT-TKBS-0027-3 Rev 01, ORAUT-TKBS-0027-4 Rev 01, ORAUT-TKBS-0027-5 Rev 01, ORAUT-TKBS-0027-6 Rev 01

Site Profile for Pacific Northwest National Laboratory

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/12/2016	02	Revision initiated to modify the scope of the PNNL site profile to reflect the decision to make no distinction between PNNL and Hanford until the year 2005. Combined the six technical basis documents into one site profile document for the period from 2005 to present. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Robert E. Burns, Jr.

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ACRONYMS AND ABBREVIATIONS

AWE	Atomic Weapons Employer
Bq	becquerel
CED	committed effective dose
CFR	Code of Federal Regulations
cm	centimeter
CRL	Capabilities Replacement Laboratory
d	day
DAC	derived air concentration
DDE	deep dose equivalent
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
DOELAP	DOE Laboratory Accreditation Program
dpm	disintegrations per minute
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EMSL	Environmental Molecular Sciences Laboratory
EPA	U.S. Environmental Agency
eV	electron-volt
F	fast (absorption type)
FFTF	Fast Flux Test Facility
ft	foot
FUA	Facility Usage Agreement
gal	gallon
HEPA	high-efficiency particulate air
HEU	highly enriched uranium
HPGe	hyperpure germanium
hr	hour
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
km	kilometer
L	liter
LLD	lower limit of detection
LSL-II	Life Sciences Laboratory II
m	meter
M	moderate (absorption type)
MDA	minimum detectable activity
MDL	minimum detection limit
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mL	milliliter

mo	month
mrem	millirem
n	neutron
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NU	natural uranium
ORAU	Oak Ridge Associated Universities
p	proton
PNNL	Pacific Northwest National Laboratory
PSF	Plutonium Storage Facility
PUREX	plutonium-uranium extraction
RTL	Research Technology Laboratory
RU	recycled uranium
RWP	radiological work permit
S	slow (absorption type)
SDE	shallow dose equivalent
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
TMA	Thermo-Analytical Incorporated
U.S.C.	United States Code
WESF	Waste Encapsulation and Storage Facility
wk	week
yr	year
α	alpha particle
µCi	microcurie
µg	microgram
§	section or sections

1.0 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in sections 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means "a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling." 42 U.S.C. § 7384l(5). On the other hand, a DOE facility is defined as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program);" and with regard to which DOE has or had a proprietary interest, or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee's eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility's designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

1.1 PURPOSE

This site profile for the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, describes aspects of the PNNL site and historical activities and practices pertinent to dose reconstruction under EEOICPA.

1.2 SCOPE

DOE and DOL have determined that, for dose reconstruction under EEOICPA, PNNL was not a separate facility from the Hanford Site until 2005. Information for performing dose reconstruction for claims that include PNNL employment before 2005 should therefore be obtained from the appropriate Project documentation for the Hanford Site.

In addition, from 2005 forward, internal and external radiation doses received within the 300 Area of the Hanford site are considered Hanford exposures, regardless if they were received in PNNL facilities in 300 Area. Nonetheless, any occupationally derived radiation dose received at Hanford from 2005 forward is valid for inclusion in a dose reconstruction for an energy employee who worked at PNNL.

Section 2.0 describes the PNNL site and facilities. It also discusses the radiological source terms present on the Hanford site as they pertain to the PNNL internal monitoring program. Section 2.0 also discusses the radiation protection program including air monitoring and area dosimetry. Section 3.0 addresses routine occupational medical X-rays. Ambient levels of radionuclides in the PNNL environment are addressed in Section 4.0 along with estimated external ambient dose rates. Sections 5.0 and 6.0 address the technical issues in relation to measurement of internal and external dose, respectively. Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 7.0.

2.0 SITE DESCRIPTION

2.1 INTRODUCTION

2.1.1 Purpose

This section briefly describes the physical environment of the PNNL site and the site activities and processes from 2005 until the present.

2.1.2 Scope

This section describes facilities on the PNNL main campus that house, or may house, operations with sealed radioactive sources, dispersible radioactive materials, or radiation generating devices. The major radiological source terms associated with the Hanford site are also addressed. Some PNNL workers routinely work on the Hanford Site, and these individuals are more likely to be monitored for occupational radiation exposure because of the relative magnitude of the radiological source terms at Hanford in relation to those at the PNNL main campus. Radiological source terms at Hanford, including PNNL facilities physically on the Hanford Site, are therefore the driver for much of the PNNL personnel monitoring practices. This section also describes the PNNL radiation protection program, including air monitoring and area dosimetry.

2.1.3 Background

PNNL is a multiprogram research institution in North Richland, Washington, just south of the Hanford Site. It conducts research in science, national security, energy, and environment in support of DOE and national strategic goals. It is operated by the Battelle Memorial Institute (Battelle) for the DOE Office of Science. Battelle has been the sole prime contractor for the management and operation of PNNL since 1965. For dose reconstruction under EEOICPA, PNNL and Hanford are considered indistinct through 2004. Information for claims that include PNNL employment before 2005 should therefore be obtained from the Hanford site profile. This PNNL site profile describes pertinent operations at PNNL from 2005 until the present.

In December 2003 DOE chartered the Pacific Northwest Site Office within the Office of Science to oversee operation of the PNNL. PNNL itself was established in 1965. PNNL is a project-based research institution. It does not engage in production operations and is not funded through large appropriations. It performs around 2,000 projects a year for DOE (including the National Nuclear Security Administration) and other agencies.

Figure 2-1 is a map of PNNL showing the core campus, the Hanford 300 Area to the north, and the 2400 Stevens Building to the south.

2.2 RADIOLOGICAL FACILITIES ON THE PNNL MAIN CAMPUS

The principal radiological facilities at PNNL are the Environmental Molecular Sciences Laboratory (EMSL), the Physical Sciences Facility (PSF), the Research Technology Laboratory (RTL), and the Life Sciences Laboratory II (LSL-II). The PSF and the RTL consist of multiple buildings. PNNL also conducts radiological work in Building 325 (the Radiochemical Processing Laboratory) and other facilities in the Hanford 300 Area. Information about Hanford facilities should be obtained from the Hanford site profile.

There have been no known, large-scale radiological incidents at PNNL from 2005 to the present. Information pertaining to radiological incidents that only impacted a limited number of individuals should be available in a worker's claim records.

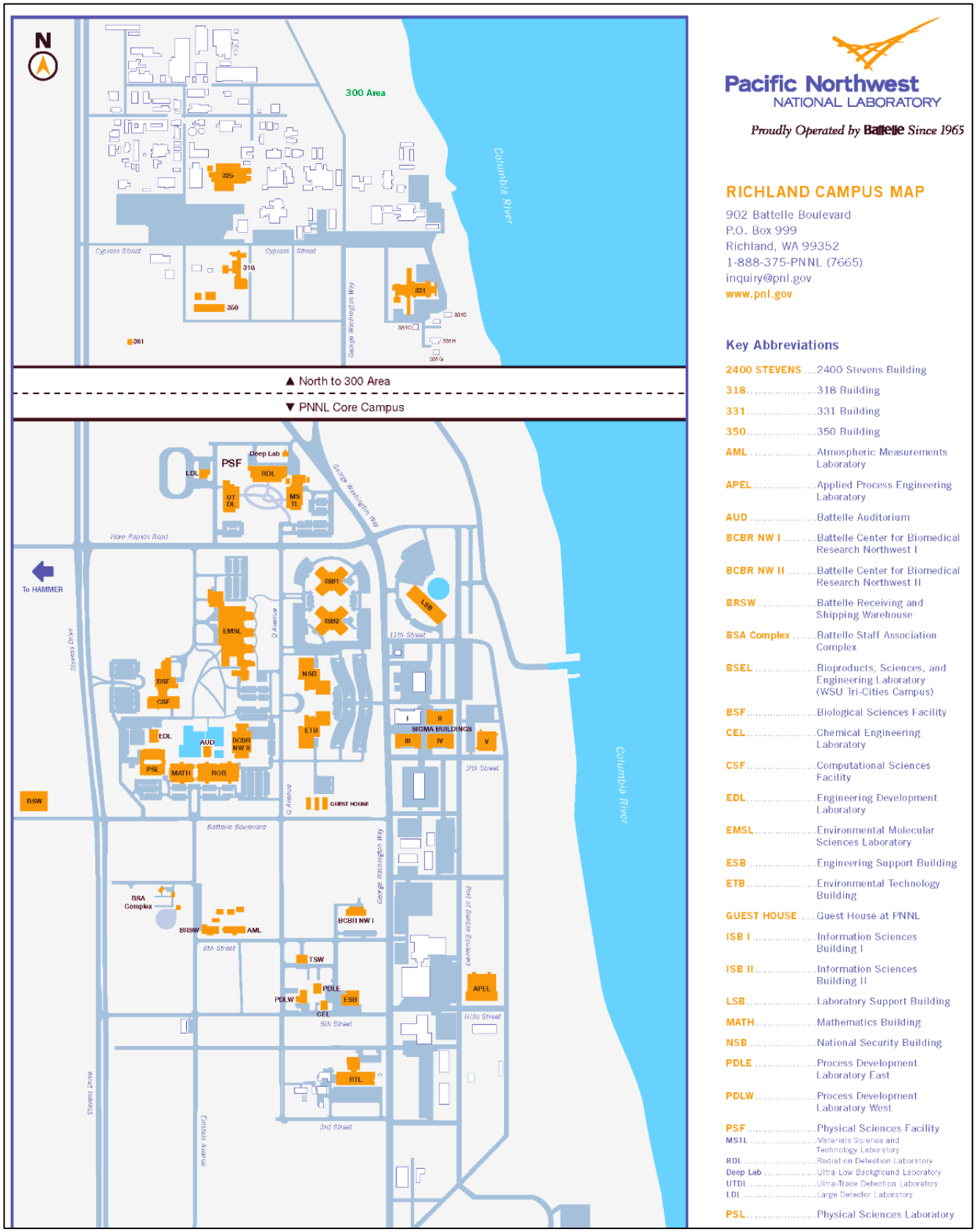

Figure 2-1. PNNL site map (part 1).

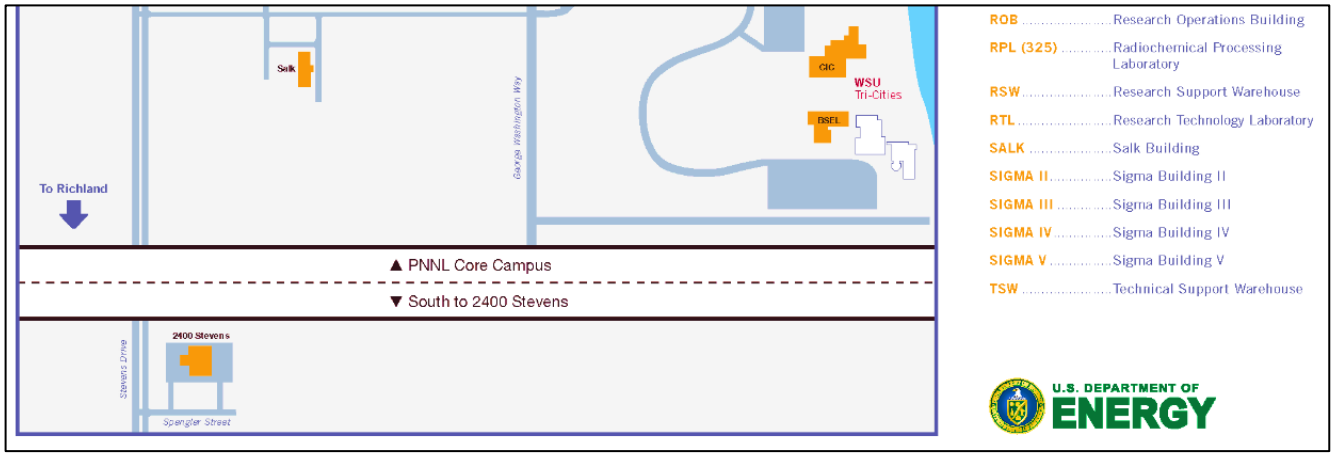

Figure 2-1. PNNL site map (part 2).

2.2.1 Environmental Molecular Sciences Laboratory

The EMSL (Building 3020) was constructed in 1997. It is a single building encompassing 224,000 gross square feet. It functions as a national scientific user facility providing experimental and computational resources to researchers from the academic community, industry, and other government laboratories (Snyder, Barnett, and Bisping 2014; BMI 2012a).

The EMSL consists primarily of offices, an auditorium, laboratories, and maintenance and storage areas. The laboratory spaces in EMSL consist of wet laboratories and computer laboratories. The wet laboratory areas were designed for work with hazardous chemical, radioactive, or biological materials. Experiments in the EMSL can involve complex systems and equipment and research animals (Snyder, Barnett, and Bisping 2014).

Research in the EMSL focuses on integrating computational and experimental capabilities. Its radiological operations are limited to sealed source use and authorized work with volumetrically released and nondispersible materials (Snyder, Barnett, and Bisping 2014).

2.2.2 Life Sciences Laboratory II

The LSL-II Building consists primarily of two laboratory floors with attached mechanical and electrical service rooms at the north and south ends. Other facilities that support LSL-II include the Chemical Storage and Transfer Facility (also known as LSL-A) and the Portable Chemical Storage Facility (also known as LSL-B).

Research in this facility includes applied research, prototype development and testing, and system validation for engineered structural materials. Mechanical design, automation, computational mechanics, and advanced materials characterization activities are also conducted in LSL-II. Some electronic technology development and wet chemical work are performed (Snyder, Barnett, and Bisping 2014).

The Facility Usage Agreement (FUA; BMI 2012b) for the LSL-II facility requires that the total quantity of radioactive material in the building be maintained below the threshold for DOE Hazard Category 3 (as defined in DOE 1997). Some workspaces within LSL-II have ventilation systems with high-efficiency particulate air (HEPA) filters, and radioactive air emissions monitoring is performed using a radioactive materials inventory tracking system (BMI 2012b).

Type I and Type II sealed radioactive sources are allowed in LSL-II, and the FUA implies that uncertified sealed radioactive sources are allowed (BMI 2012b).

Unsealed radioactive material is allowed in LSL-II but is limited to the existing inventory plus holdup. Special nuclear and fissionable materials are not allowed (BMI 2012b).

2.2.3 Physical Sciences Facility

The PSF was an element of the Capabilities Replacement Laboratory (CRL) initiative at PNNL to provide facilities and capabilities to replace those it would be losing due to the substantial clean-up activities being completed in the Hanford 300 Area. Altogether, the CRL project consisted of construction of the PSF, the Biological Sciences Facility, the Computational Sciences Facility, the Life Sciences Facility, and modifications to Hanford 300 Area Buildings 318, 325, 331, and 350.

The PSF is not a single facility, but is rather a complex of the following buildings and facilities constructed in 2010:

- 3410 Material Science and Technology Laboratory,
- 3420 Radiation Detection Laboratory,
- 3425 Ultra-Low Background Laboratory,
- 3430 Ultra-Trace Detection Laboratory,
- 3440 Large Detector Laboratory,
- 3455 Trailer A,
- 3465 Trailer B, and
- Laboratory Support Warehouse (LSW).

Trailers A and B (Buildings 3455 and 3465) and the LSW do not house radiological operations (BMI 2011a, 2011b).

2.2.3.1 Building 3410 Material Sciences and Technology Laboratory

Building 3410 is a two-story building constructed in 2010. It consists of office space, conference rooms, and common areas. The rear portion of the first floor is laboratory space. The rear portion of the second floor is mechanical space. The Central Utility Plant is attached to the north end via a common corridor. This facility includes craft shops and a receiving dock in addition to process systems (chilled water, compressed air, etc.) (BMI 2000).

Type I and Type II sealed radioactive sources are allowed in Building 3410, as are unsealed radioactive materials (within air permit limitations). Fissionable materials are allowed, but special nuclear materials are not. The FUA for Building 3410 requires that the total radioactive material inventory not exceed the threshold for DOE Hazard Category 3 (as defined in DOE 1997). However, the PSF has administrative limits that are less than the Category 3 threshold. Building 3410 has a continuously operating radioactive air confirmatory sampling system (BMI 2012c).

Building 3410 houses research capabilities associated with performance and life of materials in high-temperature, high-radiation, and corrosive environments such as those in next-generation technologies and applications in the areas of energy, construction, and transportation. Activities include work with metals, ceramics, polymeric materials, composites, and specialized coatings and surface treatments (BMI 2014).

2.2.3.2 Building 3420 Radiation Detection Laboratory

Building 3420 contains office and laboratory space that supports research in ultra-low background radiation detection. The research involves a wide variety of radionuclide measurement technologies and capabilities including state-of-the-art analytical chemistry, radiation physics, light detection,

particle detection, chromatography, scintillation materials, sorbents and “smart” materials, and field deployable instrumentation (BMI 2014).

Type I, Type II, and uncertified sealed radioactive sources are permitted in Building 3420, as are unsealed radioactive materials (within air permit limitations). Fissionable and special nuclear materials are allowed, with the latter being subject to safeguards category IV limits (BMI 2011c).

Two radioactive air permits are applicable to Building 3420. One covers laboratory spaces that are connected to a HEPA-filtered exhaust system, and the other covers laboratory and support spaces that are tied to the unfiltered exhaust system (BMI 2011c).

2.2.3.3 Building 3425 Ultra-Low Background Counting Laboratory

Building 3425 is primarily a below-grade structure that houses research in trace chemical and radionuclide detection. Also known as the Underground Laboratory or the Deep Lab, it is as much as 40 ft underground to minimize background radiation. The facility supports the development and advancement of radiation detection technologies in conjunction with research in Building 3420. Additional activities in Building 3425 include radiation physics experiments, development of ultra-low radioactivity materials, and other fundamental sciences studies (BMI 2014).

Type I, Type II, and uncertified sealed radioactive sources are permitted in Building 3425, as are unsealed radioactive materials (within air permit limitations). Fissionable materials are allowed, but special nuclear materials are not. The FUA for Building 3425 requires that the total radioactive material inventory not exceed the threshold for DOE Hazard Category 3 (as defined in DOE 1997). However, the PSF has administrative limits that are less than the Category 3 threshold. Building 3425 does not have an airborne effluent monitoring system (BMI 2010a).

2.2.3.4 Building 3430 Ultra-Trace Analysis Building

Building 3430 houses research in ultra-trace and low-level detection and characterization of radionuclides for nuclear forensics applications. Its capabilities include highly sensitive analytical systems such as mass spectrometers, optical microscopes, and electron microscopes to provide isotopic analyses and ultra-low-level radionuclide detection in a wide variety of sample matrices.

Type I and Type II sealed radioactive sources are allowed in Building 3410, as are unsealed radioactive materials. Fissionable radioactive materials are allowed, but amounts cannot exceed exempt quantities as defined in the PNNL Criticality Safety Subject Area. Special nuclear materials are allowed as long as the total does not exceed safeguards Category IV quantities.

Authorized radiation generating devices are allowed in Building 3430. The FUA for Building 3430 calls for a continuously running confirmatory radioactive airborne effluent monitoring system (BMI 2010b).

2.2.3.5 Building 3440 Large Detector Laboratory

Building 3440 houses work on the development and testing of large radiation detection systems along with testing of high-energy radiography systems (BMI 2013a).

Type I, Type II, and uncertified sealed radioactive sources are permitted in Building 3440. Fissionable and special nuclear materials are allowed, with the latter being subject to safeguards Category IV limits. Unsealed radioactive materials are not allowed in Building 3440. It has no sampling or monitoring system for radioactive airborne effluents (BMI 2013a).

2.2.4 Research Technology Laboratory

The RTL is a complex of buildings of which the main facility is Building RTL-520. RTL-520 provides laboratory, office, and storage space in support of a variety of research and development activities. Research includes chemical toxicology, environmental health physics, dosimetry, atmospheric science modeling, and soil and groundwater contamination studies. Coating and coating technologies, laser and electrochemical machining, and electrodeposition research is performed as well as research into the solid-liquid interface of geologic materials (BMI 2014).

Building RTL-530 is a small (136 ft^2) concrete block and brick storage area just west of RTL-520 for temporary storage of radioactive materials. RTL-530 includes a lead-shielded pit underneath its concrete floor for storing highly radioactive materials.

Other buildings associated with the RTL include:

- RTL 510 Chemical and Flammable Storage,
- RTL 550 Technical Services,
- RTL 560 Utility Building,
- RTL 570 Autoclave Center,
- RTL 580 Crafts Shop, and
- RTL 590 Warehouse.

The FUA for the RTL requires that the total quantity of radioactive material be maintained below the threshold for DOE Hazard Category 3 (as defined in DOE 1997). Some workspaces in RTL-520 have HEPA-filtered ventilation systems, and confirmatory air sampling for radioactive materials is performed at eight emissions points (BMI 2012d).

Type I and Type II sealed radioactive sources are allowed in RTL-520 but not in the other RTL facilities without specific authorization (BMI 2012d). Unsealed radioactive materials, special nuclear, fissionable, and high-toxicity radioactive materials are allowed in RTL-520 and RTL-530 (BMI 2012d).

Unsealed radioactive, high-toxicity radioactive, special nuclear, and fissionable materials are not allowed in other RTL facilities (BMI 2012d).

2.3 OPERATIONS WITH SPECIFIC RADIONUCLIDES AT HANFORD AND PNNL

PNNL workers would most likely encounter dispersible radioactive materials while performing duties on the Hanford Site. The methods of the PNNL internal monitoring program therefore emphasize source terms associated with facilities and operations in the Hanford 300 Area and other Hanford locations. The following sections discuss the principal radionuclides and source terms present at Hanford and PNNL.

2.3.1 Tritium

Tritium work at PNNL has included radioluminescent lights developed by the laboratory and used as a tracer or labeling compound for biological research projects. Predominant forms of tritium have been tritium oxide (tritiated water), tritium gas, and stable metal tritides in at least one project (notably zirconium tritide).

Organically bound tritium is not atypical of PNNL facilities; it is usually found in ingested foods, machinery oil from tritium operations, laboratory compounds labeled for research purposes, or wastes from other DOE facilities.

Tritiated particulate aerosols result from tritium being absorbed and retained on metal surfaces such as getters for tritium collection and storage devices (typically these are in the form of metal tritides) and as a residual contaminant in tritium production facilities. An additional possibility for tritiated particulates is tritiated metal oxides (e.g., rust and dust). A limited source of zirconium tritide metal filings was identified in 325 Building at Hanford.

The basic tool for monitoring intakes of soluble and insoluble tritium particulates is personal air sampling. Derived air concentrations (DACs) for soluble and insoluble tritiated particulates have been promulgated in 10 CFR Part 835 to aid in monitoring of workers and the workplace.

2.3.2 Cesium

Along with ^{90}Sr, ^{137}Cs is a predominant fission product isotope in source terms across Hanford. Historically, there have been ^{137}Cs production operations as well, but because of the lack of new production and radioactive decay it is no longer a significant radionuclide in Hanford source terms.

In addition to its presence in mixtures, ^{137}Cs has existed in relatively pure form at the Waste Fractionation Facility (B Plant, 221-B Building) and the Waste Encapsulation and Storage Facility (WESF, 225-B Building) in the Hanford 200 Area. Encapsulation programs at WESF have been terminated, but cesium-bearing capsules and cesium-contaminated equipment are still stored in the facility.

PNNL has found cesium to be more dispersible than strontium and that ^{137}Cs will likely constitute the major component of most intakes involving ^{137}Cs and ^{90}Sr. PNNL therefore recommends that additional bioassay appropriate for other radionuclides of concern be considered in situations where no radionuclide ratio information exists but it is suspected that ^{90}Sr or other radionuclides might be present along with ^{137}Cs.

At PNNL, bioassay for cesium is performed using whole-body counting. A 3-minute count on the NaI preview counter provides a minimum detectable activity (MDA) of 1.3 nCi for ^{137}Cs. A 10-minute count on the coaxial germanium scanning detector provides an MDA for ^{137}Cs of about 1 nCi.

Because of its relative abundance in radiological source terms at Hanford, PNNL often uses ^{137}Cs as an indicator for other nuclides, notably ^{90}Sr and plutonium. PNNL recommends annual in vivo measurements for workers who are potentially exposed to radionuclide mixtures that contain ^{137}Cs.

2.3.3 Strontium

The isotopes of dominant concern for strontium internal dosimetry are ^{90}Sr and its decay product ^{90}Y. These nuclides can be found in almost any Hanford or PNNL facility that deals with fission products or fission product waste mixtures. Most facilities that have strontium can also be expected to have other fission products present, notably ^{137}Cs, and it is a common practice at PNNL to use ^{137}Cs as an indicator of potential ^{90}Sr. However, some chemical processes at Hanford have separated cesium from strontium, and relatively pure ^{90}Sr could be associated with laboratories, waste separation facilities, and waste storage tank sludges. In particular, cesium and strontium separation operations were historically performed in the B Plant (221-B) and the WESF (225-B) in the Hanford 200 Area.

The presence of ^{89}Sr in Hanford source terms is no longer a concern, unless a new source, such as material received from off site, is introduced.

All inhalation and ingestion intakes of radiostrontium at PNNL are considered to be absorption type F. This includes fluoride forms of strontium potentially present at B Plant and WESF from the waste

fractionation and encapsulation operations that were performed there into the mid-1980s. Strontium titanate has not been used at PNNL.

A detailed study of the environmental background levels of ^{90}Sr in the urine of unexposed Hanford workers was performed in 2008 (Antonio and Rivard 2008). The study found that an environmental screening level of 1 dpm/d would imply that about 1 out of 100 workers not occupationally exposed might exceed it. For routine ^{90}Sr urinalyses, the PNNL internal dosimetry program uses a 10-mrem investigation screening level of 4 dpm/d consistent with guidance in the American National Standards Institute standard ANSI/HPS N13.39 (HPS 2001).

2.3.4 Uranium

Uranium at Hanford or PNNL can be present from a number of possible sources, including residual slightly enriched recycled uranium (RU) from the fuel cycle of the production reactors, depleted uranium (DU) from research and development projects, and various individual isotopes or mixtures associated with short-term research-scale projects. Highly enriched uranium (HEU) and natural uranium (NU) were used at Hanford in its early history, so residual contamination or buried waste containing HEU or NU could be encountered during cleanup operations.

Uranium compounds involved in historical production operations at Hanford ranged from highly soluble uranyl nitrate, to somewhat less soluble uranium trioxide, to relatively insoluble uranium oxides. Uranium hexafluoride and uranyl fluoride were not handled at Hanford.

Residual uranium contamination at Hanford generally represents the composition of the bulk of the processing over the years, which ranged from depleted to slightly enriched, based on the weight percent of ^{235}U. However, other enrichments might be encountered during cleanup of old facilities. For instance, a nondestructive analysis of gloveboxes in the 231-Z Building in 2008 found some gloveboxes with enrichments ranging from 1% to 18% (Hilliard 2008). These gloveboxes were originally used in the 308 Building. Some irradiated fuel from the Fast Flux Test Facility (FFTF) is stored in the 200 Area, but it is well contained and should not be a source of contamination. FFTF fuel had various mixtures of NU and plutonium so, if a contamination event were to occur, it would be necessary to get ratios of uranium and plutonium isotopes from the contamination itself. Uranium-233 was separated and handled during the thorium extraction campaigns at the Plutonium-Uranium Extraction (PUREX) Plant in 1965, 1966, and 1970. HEU fuel slugs were used in some Hanford production reactors from 1949 to 1958. These compositions might also be encountered during clean-up operations. See the Hanford site profile for information on isotopic ratios and content of other constituents present in uranium source terms at Hanford.

PNNL considers single, acute intakes of uranium to be the most likely scenario, although chronic exposure to low levels of uranium contamination in soil is possible during excavation operations. The exposure period for such operations is typically days or weeks, and intakes are monitored via air sampling.

2.3.5 Plutonium

Plutonium can be found in nearly all Hanford facilities, including waste handling facilities and tank farms. Plutonium can also be found at Hanford and PNNL as a result of PNNL research projects that involved spent fuel from nuclear power plants, breeder reactor applications, and radioisotope applications. Many of these research projects were in 300 Area facilities. Analytical chemistry laboratories might contain plutonium standard solutions.

Pure isotopes of plutonium are seldom encountered at Hanford or PNNL facilities. Plutonium mixtures at Hanford and PNNL generally fall into one of two categories:

- Weapons-grade plutonium having a nominal ^{240}Pu content of 6% by mass, and
- Fuel-grade plutonium having a nominal ^{240}Pu content of 12% by mass.

A third category, commercial reactor grade, also exists. This material originates from nuclear power reactor fuel cycles and contains higher amounts of ^{240}Pu (e.g., 25% by weight) than the weapons- or fuel-grade mixtures. Commercial reactor grade plutonium would be associated with research projects involving commercial reactor fuels, such as the Nuclear Waste Vitrification Project in the 1970s.

The Hanford site profile contains isotopic mixture information for weapons-grade, fuel-grade, and commercial reactor grade plutonium as a function of age. The Hanford site profile should also be reviewed for information on the appropriate absorption type to assign for a given case.

2.3.6 Americium

Americium is found at Hanford as the ingrown ^{241}Am progeny of ^{241}Pu in a plutonium mixture or as a separated ^{241}Am isotope that exists singly or in combination with other separated isotopes in waste mixtures or laboratory facilities. In addition, ^{243}Am has been used in some PNNL facilities as a research isotope. Both ingrown and separated ^{241}Am were historically present at the Hanford Plutonium Finishing Plant (Building 234-5Z) and associated facilities.

Separated ^{241}Am is also a trace contaminant in many of the 200 Area tank farm waste mixtures. It is not likely that tank farm waste would contain separated ^{241}Am as a pure isotope; it can be anticipated that it would be accompanied by much larger quantities of fission product activity. However, there have been isolated discoveries of relatively pure ^{241}Am in tank farm related facilities (Maclellan 2013).

Pure isotopes of ^{241}Am and ^{243}Am can be found in analytical laboratory standard solutions and in pure isotope research applications.

2.3.7 Trace Radionuclides and Radionuclide Mixtures

Radionuclide mixtures at Hanford can be found in reactor facilities, former chemical separations and processing facilities, waste management facilities, and laboratories. The radionuclides most commonly encountered in mixtures are ^{137}Cs, ^{90}Sr, and plutonium. PNNL bioassay capabilities therefore consider assessment of intakes for mixtures of ^{137}Cs and ^{90}Sr, ^{137}Cs and plutonium, and ^{90}Sr and plutonium.

PNNL internal dosimetry methods for radionuclide mixtures make use of established radionuclide ratios in the case of well-characterized sources, but in other cases the detection of a nuclide that might be a component of a mixture is used to trigger supplemental bioassay for other, potentially significant, radionuclides.

Mixtures of ^{137}Cs and ^{90}Sr

Mixtures of ^{137}Cs and ^{90}Sr are particularly common in the Hanford 200 Area tank farms. Given the wide variety of waste treatment methods that have been applied at Hanford over the years, a 1-to-1 ratio of ^{137}Cs to ^{90}Sr (reflecting their intrinsic fission yields from uranium fuels) should not be assumed. PNNL asserts that an annual whole-body count using the preview counter meets their goal of a minimum detectable dose of 100 mrem committed effective dose (CED) for ^{137}Cs:^{90}Sr activity ratios of up to approximately 1:30. If the coaxial germanium counter is used for whole-body counts the ^{137}Cs:^{90}Sr activity ratio corresponding to 100 mrem CED improves to 1:40. PNNL states that workers

with the potential for exposure to mixtures of ^{137}Cs and ^{90}Sr where the ratio of ^{90}Sr to ^{137}Cs exceeds 30 (nominally) should be considered for supplemental bioassay for strontium.

Mixtures of ^{137}Cs and Plutonium

Mixtures of ^{137}Cs and plutonium can be found in Hanford facilities associated with spent fuel management and in waste streams from such facilities. Examples include the spent fuel basins, fuel processing hot cells, and waste tank sludges. Mixtures of ^{137}Cs and plutonium are likely to be predominantly ^{137}Cs on an activity basis, but a wide range of ^{137}Cs:plutonium ratios is possible, from 1,000:1 to 1:1. PNNL states that determining the absorption of the plutonium for such mixtures is problematic and acknowledges that the minimum detectable dose associated with lower ^{137}Cs:plutonium activity ratios (i.e., mixtures with higher plutonium content) and annual in vivo counting for ^{137}Cs can be large, especially for type S plutonium. PNNL therefore recommends supplemental plutonium bioassay for workers with the potential for exposure to mixtures of ^{137}Cs and plutonium where the ^{137}Cs:plutonium activity ratio is approximately 30 or less.

Mixtures of ^{90}Sr and Plutonium

Mixtures of ^{90}Sr and plutonium are considered most likely to occur in tank farm facilities at Hanford, probably associated with contamination from waste tank sludges. For its assessments of minimum detectable dose, PNNL assumes the ^{90}Sr is type F and the plutonium is type M, consistent with the nitrate nature of most waste tank contents. PNNL acknowledges the possibility that dry plutonium contamination that is exposed to dry air and a normal building or outdoor temperature environment can undergo gradual oxidation over time and approach a type S material, but asserts that the use of type M dose coefficients for plutonium provides a conservative approach to the estimations of minimum detectable dose based on using ^{90}Sr as a tracer radionuclide.

PNNL recommends that workers be considered for supplemental bioassay for plutonium (in addition to strontium) if there is potential for exposure to mixtures where the ^{90}Sr:plutonium activity ratio is about 100 or less.

2.4 PNNL RADIOLOGICAL PROTECTION PROGRAM

PNNL implements the occupational radiation protection requirements of 10 CFR Part 835 and applicable DOE directives through a radiation protection program designed after the DOE Radiological Control Manual (DOE 1992). The current program is detailed in the PNNL *Radiation Control Program Description* published in April 2013 (BMI 2013b). Radiological support is provided to PNNL line managers and workers by the Radiation Protection Division. PNNL radiation protection personnel are expected to receive day-to-day priorities from facility managers.

Consistent with 10 CFR Part 835, general employees who have not completed appropriate training, examinations, and performance demonstrations are not permitted unescorted access to any radiological area at PNNL. Radiological workers are the only individuals expected to receive greater than 100 mrem in a year. The majority of monitored workers at PNNL do not receive measurable doses.

In general, all radiological work at PNNL is project-based. Radiological work permits (RWPs) therefore serve as the principal means for informing workers of area radiological conditions and entry requirements and to provide a mechanism for relating worker exposure to specific work activities.

PNNL mandates the use of RWPs to control the following activities:

- Entry into radiological areas,
- Handling of materials with removable contamination that exceed established limits,

- Work in localized benchtop areas, laboratory fume hoods, sample sinks, and containment devices that have the potential to generate contamination in areas that are otherwise free of contamination,

- Work that disturbs the soil in soil contamination areas, and

- Work that involves digging in underground radioactive material areas.

The PNNL radiation control program description states RWPs should include the following information unless the information is already included in related work documents (BMI 2013b):

- Dosimetry requirements including any bioassay requirements,
- Prejob briefing requirements as applicable,
- Training requirements for entry,
- Protective clothing and respiratory protection requirements,
- Radiation protection coverage requirements and stay time controls as applicable,
- Limiting radiological conditions that might void the RWP,
- Special dose or contamination reduction considerations, and
- Special personnel frisking considerations.

PNNL uses three different types of RWPs. Laboratory-wide RWPs are used for entry and repetitive work in areas with low-hazard radiological conditions. Owner-specific RWPs are used for entry and repetitive work in areas with low-moderate hazard radiological conditions. Job-specific RWPs are used for more complex work and for entry into high-hazard areas.

Laboratory-wide and owner-specific RWPs can be used to control routine or repetitive activities, such as tours and inspections or minor work activities outside of areas with engineered controls (e.g., fume hood or glovebox), in areas with well-characterized and stable radiological conditions, or for work inside areas with engineered controls that contain moderate hazard radiological conditions. Job-specific RWPs are recommended to control nonroutine operations or work in areas with changing radiological conditions.

PNNL has an ALARA (as low as is reasonably achievable) committee, one of the functions of which is to determine the applicable administrative dose limits for PNNL and reassess them annually based on an evaluation of historical and projected radiation exposures, workload, and mission. A tiered system of limits is established under which approval from higher levels of management is needed to exceed a given limit. The four tiers of PNNL administrative dose limits as of April 2013 are given in Table 2-1.

Table 2-1. PNNL administrative dose limits as of April 2013 (mrem).

Tier	Total effective dose	Skin/extremity	Lens of eye	Any organ
1	500	15,000	4,500	15,000
2	1,000	22,500	6,750	22,500
3	1,500	30,000	9,000	30,000
4	2,000	Not applicable	Not applicable	Not applicable

An administrative limit on lifetime total effective dose is also in place. It is equal to an individual's age times 1,000 mrem.

2.4.1 PNNL Air Monitoring Program

Consistent with 10 CFR Part 835, the PNNL radiation protection program mandates that monitoring for airborne radioactivity be performed under the following circumstances (Stoetzel 2012):

- An individual is likely to receive an exposure of 40 or more DAC-hr in a year, or
- As necessary to characterize the airborne radioactivity hazard where use of respiratory protective devices has been prescribed.

In addition, the PNNL radiation protection program requires that real-time (or continuous) air monitoring be performed as necessary to detect and provide warning of airborne radioactivity concentrations that warrant immediate action to terminate inhalation of radioactive material (Stoetzel 2012).

Workplace air sampling and monitoring at PNNL consist of fixed-location air sampling, job-specific sampling, and real-time air monitoring.

Fixed-location air samplers consist of a sample head and a particulate filter connected to a vacuum source, which is often a building vacuum system. If needed, portable, giraffe-type air samplers are used for fixed-location monitoring in remote areas not served by a building vacuum system. Fixed-location air sampling is required in occupied areas where a worker is likely to receive an annual exposure of 40 DAC-hr or more under normal work conditions, or for entry into posted airborne radioactivity areas.

Job-specific air sampling involves the collection of prejob, during-job, and postjob air samples, as appropriate. Prejob samples can be used to establish radon progeny concentrations or verify prejob conditions or postings. During-job sampling is used as needed to estimate worker DAC-hr exposures and to verify respiratory protection requirements. Postjob sampling can be used to verify appropriate conditions for down-posting (i.e. reducing the posted radiological hazards and entry requirements). Job-specific air sampling is required during work in posted airborne radioactivity areas, during breach of contaminated systems or components (e.g., gloveboxes or hot cells), and during whole-body entries into high-contamination areas or work on equipment with high levels of removable contamination. Job-specific air sampling is performed using low-volume, high-volume, or lapel air samplers, as appropriate. Kinetic impactors might also be used for particle size studies.

Real-time air monitoring is required where there is potential for concentrations of airborne radioactivity that would warrant immediate action to terminate inhalation of radioactive material. Typical locations include near gloveboxes that contain highly radiotoxic materials; in storage rooms used to store potentially dispersible, highly radiotoxic materials; near doorways to hot cell airlocks; and near hot cell transfer mechanisms or ports. Real-time air monitoring at PNNL is performed using alpha, beta, or tritium continuous air monitors, as appropriate.

DAC-hr tracking is performed for all jobs requiring during-job air sampling. The need for DAC-hr tracking is also evaluated for fixed-location air sample results that exceed 2% of a DAC. Table 2-2 summarizes follow-up actions triggered by DAC-hr estimates for single intakes and for cumulative exposure over a calendar year. PNNL does not track DAC-hr estimates that are less than 1 DAC-hr.

When performing dose evaluations triggered by DAC-hr estimates, the PNNL internal dosimetry staff makes a determination about the representativeness of the job-specific air sampling results. All lapel monitoring results are considered representative. Likewise, samples collected within 1 ft of the individual's nose and mouth are considered representative unless they are invalidated by cross contamination or other factors. Samples not in the immediate vicinity (within 1 ft) of the worker's nose and mouth, but collected from a location between the worker(s) and the release point, are

considered representative on the basis the result should be conservative. If necessary, airflow testing can be performed in cases when air samples do not meet these representativeness criteria to determine if a sample can be considered representative or if correction factors are needed.

These same representativeness criteria are applied regardless if dose is being assigned from job-specific air sampling results or from fixed-location (continuous) air monitoring. In some instances elevated continuous air monitoring results can be caused by a job in that local area that required job-specific air sampling. If so, then the DAC-hr estimates from the job-specific monitoring are used in lieu of those from the continuous air monitors.

2.4.2 PNNL Area Dosimetry Program

In January 1993 PNNL established an area monitoring dosimeter program in accordance with Article 514 of the DOE Radiological Control Manual (DOE 1994). The purpose of the program was to

Table 2-2. Follow-up actions triggered by elevated DAC-hr estimates.

Type of exposure	DAC-hr estimate	Follow-up actions
Acute (single intake)	1 to <10	Assign dose directly from DAC-hr estimate or conduct special bioassay. The DAC-hr estimate is entered into the DAC-hr tracking system if bioassay is not performed.
Acute (single intake)	10 to ≤40	Further analyze the air sample to determine the isotopic mix and better define the potential exposure. Conduct special bioassay and dose evaluation as deemed appropriate by PNNL internal dosimetry staff. The DAC-hr estimate is entered into the DAC-hr tracking database if bioassay is not performed.
Acute (single intake)	>40	Initiate an internal dosimetry investigation. Further analyze the air sample to determine the isotopic mix and better define the potential exposure. Conduct special bioassay and perform an internal dose evaluation.
Cumulative in one calendar year	≤10	Enter the DAC-hr estimate into the DAC-hr tracking system and verify that the worker is on appropriate bioassay. The DAC-hr estimate is deleted from the tracking system once bioassay results are received or a permanent dose is recorded based on the DAC-hr estimate.
Cumulative in one calendar year	>10	Enter the DAC-hr estimate into the DAC-hr tracking system and verify that the worker is on appropriate bioassay. PNNL internal dosimetry determines if internal dose evaluation is needed. The DAC-hr estimate is deleted from the tracking system once bioassay results are received or a permanent dose is recorded based on an internal dose evaluation.

demonstrate that external radiation doses to individuals in certain areas did not exceed established thresholds and, therefore, that personnel dosimetry in those areas was not required.

The PNNL radiological control program requires personnel dosimetry for:

- Radiological workers who are likely to receive at least 100 mrem annually, and
- Declared pregnant workers, minors, and members of the public who are likely to receive at least 50 mrem annually.

The area dosimeters were exchanged and analyzed quarterly or annually depending on the location. For 2007 through 2011 the dosimeters were the Hanford standard dosimeter (Harshaw Model 8825) and the Hanford combination neutron dosimeter. The area dosimetry program was expected to transition to the Landauer InLight Model 2 and Model 2T optically stimulated dosimeters in 2012

(Bivins and Stoetzel 2012) but it is unknown if this actually occurred. PNNL transitioned to the same Landauer dosimeters for personnel monitoring as of January 2013 (see Section 6.0).

The standard dosimeter was used in all monitored locations. Some locations were also monitored with neutron dosimeters in addition to the standard dosimeters. Neutron dosimeters were mounted on 5-gal carboy bottles to allow for albedo response.

Investigation levels for area dosimeter results were 40 mrem for quarterly reads and 160 mrem for annual reads for 2007 through 2009. In 2010 the investigation levels were increased to 50 mrem for quarterly exchange and 200 mrem for annual exchange. The investigation levels reflect an assumed occupancy rate of 2,000 hours per year, which equates to an occupancy fraction of 0.23 (given a year defined as 8,760 hours). Applying the assumed occupancy yields threshold values of 54 mrem per quarter and 217 mrem per year to reach 50 mrem in a 2,000 hour working year.

In addition to the above occupancy fraction (0.23), PNNL also applies an occupancy factor when evaluating the area dosimeter readings relative to its 50-mrem threshold. The occupancy factor is defined so that a value of 1.0 equals 2,000 hours of occupancy in a year. PNNL also applies a background correction to the dosimeter readings, so the assigned annual dose results represent net values. A neutron correction factor is applied to neutron dose readings to account for the difference between the unmoderated neutron spectrum used for dosimeter calibration and the moderated or scattered neutron spectrum present in the monitoring locations.

The selection criteria for locations for area dosimetry monitoring were as follows:

- All PNNL facilities in the Hanford 300 Area where staff worked at least 8 hours per month,
- All PNNL facilities where staff performed radiological work (i.e. had a current radiological work permit), and
- All PNNL facilities within 15 m of another facility (including Hanford contractor facilities) that contained an indoor or outdoor radiological area.

Locations were selected for neutron monitoring as needed. Note that “PNNL” in this context is from the Laboratory’s perspective. PNNL facilities within the Hanford 300 Area are considered Hanford facilities under EEOICPA.

None of the area dosimetry results for 2007 through 2011 exceeded 50 mrem in a year after correcting for occupancy. Information about the number of monitored locations and those selected for neutron monitoring is summarized below. This information was sourced from the annual reports from the PNNL area dosimetry program for 2007 through 2011 as noted below:

- 2007. 132 locations were monitored using the standard dosimeter. Additional neutron monitoring was performed in three locations in the Hanford 300 Area: one in Building 318 and two in Building 325 (Bivins and Stoetzel 200e8).
- 2008. 135 locations were monitored using the standard dosimeter. Additional neutron monitoring was performed in three locations in the Hanford 300 Area: one in Building 318 and two in Building 325 (same locations as the year prior) (Bivins and Stoetzel 2009).
- 2009. 135 locations were monitored using the standard dosimeter. Additional neutron monitoring was performed in three locations in the Hanford 300 Area: one in Building 318 and two in Building 325 (same locations as the year prior) (Bivins and Stoetzel 2010).

- 2010. 176 locations were monitored using the standard dosimeter. Additional neutron monitoring was performed in seven locations in the Hanford 300 Area and one location in the EMSL on the PNNL main campus. Neutron monitoring was performed in Building 318 (one location), Building 325 (two locations), Building 331 (four locations), and the EMSL (one location in Room 1344). The monitoring in the EMSL was prompted by a ^{252}Cf sealed source stored in a safe in Room 1344 (Bivins and Stoetzel 2011).

- 2011. 154 locations were monitored using the standard dosimeter. Additional neutron monitoring was performed in seven locations in the Hanford 300 Area, one location in the EMSL, and one location in Building 3440. The Hanford 300 Area and EMSL neutron monitoring locations were the same as those monitored in 2010. For 2011 an additional neutron area dosimeter was placed in Building 3440 due to neutron sources in a safe in Room 1303 (Bivins and Stoetzel 2012).

3.0 OCCUPATIONAL MEDICAL DOSE

Occupational medical services for PNNL employees, including all medical X-rays required as a condition of employment, were provided by the Hanford site contractor from January 1, 2005, through September 30, 2012. Dose reconstruction information for energy employees that had PNNL employment during that period should therefore be obtained from ORAUT-TKBS-0006-3, *Hanford Site – Occupational Medical Dose* (ORAUT 2010).

Since October 1, 2012, occupational medical X-rays for PNNL employees have been performed at the Kadlec Medical Center in Richland, Washington. Kadlec Medical Center is not a covered facility under EEOICPA for this time period; therefore, radiation dose from occupational screening X-rays after September 30, 2012, should not be included in dose reconstructions.

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

4.1 INTRODUCTION

4.1.1 Purpose

This section addresses the occupational environmental dose applicable to the PNNL site from 2005 to the present. Occupational environmental dose refers to the radiation dose a worker received outside of buildings, but on the PNNL site, as a result of ambient airborne radionuclides or ionizing radiation.

4.1.2 Scope

Internal and external exposures to radionuclides in the outdoor environment are considered separately in Sections 4.2 and 4.3, respectively.

4.2 INTERNAL DOSE FROM ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

Both the Hanford and PNNL sites release airborne radioactive materials to the air as a result of operations. Both sites, therefore, engage in routine airborne effluent monitoring and issue annual reports detailing airborne releases and the associated radiation dose to workers and members of the public. These reports are provided, in part, to demonstrate compliance with U.S. Environmental Agency (EPA) and State of Washington requirements that the dose to a member of the public from radioactive air emissions not exceed 10 mrem/yr. Compliance is shown by calculating the dose to the nearest receptor or to an otherwise hypothetical maximally exposed individual. The dose calculations are performed using the site's airborne effluent monitoring and local meteorological data as inputs to EPA-approved computer programs for that purpose.

From 2005 through 2009, the only radioactive air emissions from PNNL were associated with two Battelle-owned facilities, the main building of the RTL (RTL-520) and the LSL-II. During that time PNNL issued separate annual airborne emissions reports for PNNL facilities, which were limited to the EMSL and the Battelle-owned buildings. The Battelle-owned facilities operated under a radioactive materials license from the State of Washington.

As of 2010, several radiological facilities in the PSF complex came online. PNNL therefore began issuing an annual radionuclide air emissions report to address those facilities. It also continued to provide the annual airborne emissions reports for the two Battelle-owned facilities (RTL and LSL-II).

The Hanford site has provided annual radionuclide air emissions reports and detailed environmental reports since before 2005.

In addition to airborne releases from Hanford and PNNL, individuals on the PNNL campus might also be exposed to radioactive airborne effluents from a number of commercial facilities that operate on the Hanford Site and in and around Richland, Washington. These include the Columbia Generating Station (a commercial nuclear power reactor) operated by Energy Northwest, a low-level radioactive waste disposal facility operated by US Ecology, a nuclear fuel fabrication facility operated by AREVA, and other commercial waste handling and decontamination facilities. The annual compliance calculations performed by both Hanford and PNNL are based on measured effluent data and therefore do not reflect potential dose from other, non-DOE sources.

Table 4-1 presents annual calculated doses that demonstrate compliance with the 10-mrem/yr limit for radioactive airborne emissions from the Hanford Site, Battelle-owned buildings within the PNNL campus, and from the PNNL radiological facilities within the PSF complex (notably Building 3410). For the separately reported Battelle-owned facilities at PNNL, the calculated dose from the LSL-II is

negligible relative to that from the RTL. Those contributors are therefore denoted in the table as PNNL – RTL. References are given for each annual dose value. The asserted doses are effective dose equivalent.

Table 4-1. Annual doses from radioactive airborne emissions reported by Hanford and PNNL (mrem).

Year	Hanford[a]	PNNL – RTL[b]	PNNL – PSF[c]
2005	0.039	0.3	Not applicable
2006	0.10	0.3	Not applicable
2007	0.14	0.3	Not applicable
2008	0.11	0.5	Not applicable
2009	0.068	0.5	Not applicable
2010	0.075	0.6	8.0E-06
2011	0.042	4.6E-04	1.7E-05

a. Sources for Hanford values by year: Diediker et al. (2006) and Rokkan et al. (2007, 2008, 2009, 2010, 2011, 2012).
b. Sources for RTL values by year: Anderson (2006, 2007, 2008, 2009, 2010, 2011, 2012).
c. Sources for PSF values by year: Snyder et al. (2011), Snyder, Barnett, and Bisping (2012).

The reported annual dose values for Hanford include inhalation dose from routine and nonroutine point source emissions, plus that from diffuse and fugitive sources including radon. They represent the inhalation dose to a hypothetical maximally exposed individual 1.4 km east of the 300 Area on the east side of the Columbia River.

The relatively higher annual dose values for the RTL are due to the low elevation of the release point (5 m) and the close proximity of the assumed receiver (300 m in 2005 to 2007 and 200 m in 2008 to 2011). The reported dose values for the RTL also include contributions from pathways other than inhalation. The significant decrease in the reported dose for 2011 in relation to previous years appears to be due to a decrease in the amount of ^{137}Cs that was released.

There were no radioactive airborne releases from other PNNL facilities until 2010, when several facilities in the PSF complex began radiological operations. The major defined emissions points for the PSF complex are the 3410, 3420, and 3430 buildings. All of these facilities discharge radioactive airborne effluents through stacks ranging in height from 13.5 m to 15.5 m. The effective discharge heights are greater. For 2010, the location for the maximally exposed individual was a location 480 m south-southeast of Building 3410 (Snyder et al. 2011). In 2011 this distance was increased to 550 m due to a change in the stack operating parameters (Snyder, Barnett, and Bisping 2012).

The data in Table 4-1 show that inhalation doses to PNNL workers from radioactive airborne effluents from Hanford or PNNL are trivial and can be neglected for dose reconstruction purposes. Calculated annual environmental internal doses that total less than 0.001 rem for a specific radiation type and energy interval are not required to be included in the Interactive RadioEpidemiological Program (IREP) input sheet (ORAUT 2004). For such cases, the dose reconstruction should include appropriate discussions.

4.3 EXTERNAL EXPOSURE FROM ONSITE AMBIENT SOURCES

Before 2006, the environmental program implemented by the Hanford Site contractors included the deployment of environmental TLDs for measuring the ambient external dose in a number of locations on and around the site. The locations included some on the PNNL main campus. The Hanford environmental external dose monitoring was discontinued after 2005 due to funding reductions. The Hanford Site environmental report for 2006 notes that the many years' worth of external dose data "indicate that current radiation levels are at or near background levels, and are stable or decreasing as onsite cleanup activities progress" (Poston et al. 2007).

Table 4-2 shows the reported ambient external dose data for 2005 for locations on the Hanford Site and its perimeter, corrected from continuous occupancy to a period of 2,000 hours (Poston et al. 2006, Tables 10.13.4 and 10.13.5). The values in the table represent the maximum values in the environmental report, which are the highest readings obtained for the measurements within a given distance classification (i.e., for a given area).

Table 4-2. Annual dose rates (mrem/yr) for the PNNL main campus and Hanford site locations.

PNNL	100 Area	200 Area	300 Area	400 Area	600 Area	Sitewide (Hanford)
22	21	22	20	20	23	23

The values for the PNNL main campus are those reported for the 11 Hanford perimeter locations. The data for the Hanford Site itself are included for cases in which a location other than the PNNL main campus might be indicated. The annual dose rates in Table 4-2 should be used for all years from 2005 to the present.

5.0 INTERNAL DOSIMETRY

5.1 INTRODUCTION

5.1.1 Purpose

The purpose of this section is to describe internal dosimetry practices at PNNL to support dose reconstructions under EEOICPA.

5.1.2 Scope

Between January 1, 2005, and September 30, 2012, PNNL and Hanford shared the same internal monitoring program. PNNL managed those services for the Hanford site contractors. As of October 1, 2012, internal monitoring at Hanford was taken over by its mission support contractor. PNNL purchased internal monitoring services from that contractor for the remainder of 2012 before transitioning to its own program as of January 1, 2013. Internal dosimetry information for PNNL workers should therefore be obtained from the Hanford site profile for the period from January 1, 2005, through December 31, 2012.

The information in the remainder of this section pertains to the PNNL internal dosimetry program from January 1, 2013, to the present. Although the PNNL internal monitoring program then became separate from the Hanford program, PNNL and Hanford still used the same contractor (GEL Laboratories) for in vitro analyses. PNNL also still used the Hanford in vivo counting facilities.

Section 5.2 describes the PNNL internal dosimetry program in general and how individuals are selected for bioassay. Section 5.3 discusses the in vitro and in vivo monitoring methods and the sensitivities of those measurements. Internal dosimetry records are discussed in Section 5.4, and Section 5.5 presents tables that define codes in the databases PNNL uses for its internal monitoring and dose evaluation records.

Except as otherwise noted, all information in this section was derived from (Maclellan 2013) and (BMI 2013c).

5.2 PNNL INTERNAL DOSIMETRY PROGRAM

Like other site services, PNNL radiation protection services are provided under a tenant model under which users acquire needed services on a fee basis. The internal dosimetry program offers the following services to PNNL employees and contractors who are monitored under the PNNL radiation protection program:

- Administering the bioassay monitoring program,
- Investigating and documenting evaluations of potential intakes for exposure records files,
- Arranging for in vitro analysis services and ensuring that the analytical services contractor conforms to contractually specified technical requirements,
- Maintaining DOE Laboratory Accreditation Program (DOELAP) accreditation for in vitro analyses (accreditation for in vivo analyses is maintained by the Hanford in vivo monitoring program, under which PNNL maintains a secondary accreditation),
- Selecting and applying models, procedures, and practices for evaluating internal radionuclide depositions and doses, and

- Providing guidance and support to PNNL in technical matters pertaining to internal dosimetry.

The primary means of identifying potential radionuclide intakes at PNNL are air sampling, contamination surveys, and other field monitoring techniques. Bioassay is considered the primary means for confirming intakes and a secondary means for identifying intakes.

The internal monitoring program is designed to be able to identify and confirm an intake resulting in a CDE of 100 mrem. For some materials, such as plutonium or type S uranium, detecting intakes that would result in this dose requires nonroutine bioassay that is triggered promptly by workplace monitoring.

5.2.1 Routine Bioassay

As of June of 2013, no PNNL workers were on a routine bioassay schedule. Rather, PNNL adopted a modified version of the process (HPS 2001, Appendix A) to identify workers who require bioassay. This approach is based on potential dose per occupancy day, which is derived from information in RWPs. Bioassay is required for any radiation worker whose work history for the past 12 months indicates the potential for intake of radioactive material sufficient to result in a CDE of 100 mrem or more from all radionuclides. A unity rule approach is used if a worker is expected to work under multiple RWPs. If the assessment of the potential dose per occupancy day indicates a need for internal monitoring, then bioassay requirements are assigned based on the radionuclides the individual will be working with. Bioassay intervals are assigned for each radionuclide or group of nuclides that indicate the time since the potential intake during which a valid bioassay result should be obtained.

The need for bioassay is monitored routinely via the Bioassay Management Tool, which is used to perform monthly reviews of radiologically controlled area entries in conjunction with information from RWPs. Derived air concentrations, annual limits on intake, occupancy factors, dispersibility factors, etc. all factor in to the determination of whether bioassay is required. The DAC-hr tracking requirements and action levels are discussed in Section 2.4.1.

If the Bioassay Management Tool identifies the need for bioassay, one or more selections are made from the bioassay categories in Table 5-1 based on radionuclide information from the RWPs. In general, PNNL assumes that no more than four bioassay analyses will be needed to monitor for the mixtures of radionuclides to which its staff might be exposed. PNNL makes use of indicator radionuclides in determining bioassay requirements for established radionuclide mixtures. Table 5-2 gives the analysis codes that correspond to the bioassay categories shown in Table 5-1. The analysis codes in Table 5-2 do not include all analysis types. See Tables 5-3 through 5-8 for a complete listing of analysis codes.

Bioassay is not available for the bioassay category codes Remainder and AC227. The PNNL guidance in these instances is to “document equivalent monitoring action.” The radium isotopic analysis (IRA in the tables) is not included in the contractual detection level data, which indicates this analysis is not currently available.

Table 5-3 presents the same information as Table 5-2 but formatted to show the analysis codes that can be associated with a given bioassay category.

In addition to the potential dose per day approach described above, PNNL might in some instances implement routine bioassay for PNNL workers who are working at other sites where there is a potential for radioactive material intake.

Table 5-1. PNNL bioassay category codes and intervals.

RWP radionuclide	Bioassay category code	Bioassay interval (mo)
H-3	Tritium	3
H-3-tritide	Tritide	3
Pu-238, Pu-239	IPU	12
Cm-242, Cm-244	ICM	12
Cs-137, Co-60, MFAP,[a] tank waste	Gamma	12
Ra-224, Ra-226	IRA	12
Sr-85, Sr-89, SR-90	SR	12
Th-228, Th-229, Th-230, Th-232	ITH	12
U, U-234, U-235, U-238, UDEP, UNAT	IUS	3
U, U-234, U-235, U-238, UDEP, UNAT	IU	12
Ac-227	AC227	12
Np-237	NP237	12
Am-241	AM241	12
Am-243	AM243	12
Any nuclide not in the above groups	Remainder	12

a. MFAP = mixed fission or activation products.

Table 5-2. Bioassay analysis codes and the corresponding bioassay categories.

Analysis code	Analytes or analysis	Applicable bioassay categories
H3	Tritium	Tritium, tritide
SR	Total strontium	SR
SR90	Sr-90	SR
NP237	Np-237	NP237
AM241	Am-241	AM241
AM243	Am-243	AM243
IPIU	Sequential: Pu isotopic + U isotopic	IPU
ICM	Cm-242, Cm-244	ICM
IPA	Sequential: Pu isotopic + Am-241	IPU, AM241
ITPAC	Sequential: Pu isotopic + Am-241 + Cm isotopic	IPU, ICM, AM241
IPSA	Sequential: Pu isotopic + Am-241 + Total strontium	IPU, SR, AM241
IUPU	Sequential: Pu isotopic + U-238	IPU
IPS	Sequential: Pu isotopic + Total strontium	IPU, SR
IPU	Pu isotopic	IPU
IRA	Ra isotopic	IRA
ITH	Th isotopic	ITH
IU	U isotopic	IUS, IU
ICA	Sequential: Cm isotopic + Am-241	ICM
GAMMA	Gamma spectroscopy	GAMMA
WB	Whole-body counting	GAMMA

5.2.2 Baseline and Termination Bioassay

Not all PNNL workers receive baseline or termination bioassays. Baseline bioassays might be ordered for personnel who have had previous intakes that might interfere with interpretation of future bioassay results or who have the potential to receive intakes of radioactive materials that might be present in urine from nonoccupational sources (e.g., uranium).

Termination bioassay is required for workers who participated in or qualified for participation in bioassay monitoring, unless it is documented that the worker was not potentially exposed to dispersible radioactive materials after the most recent bioassay or if a special evaluation of the

Table 5-3. Bioassay analyses applicable to each bioassay category.

Bioassay category	Applicable analysis codes
Tritium	H3
Tritide	H3
IPU	IPIU, IPA, ITPAC, IPSA, IUPU, IPS, IPU
ICM	ICM, ITPAC, ICA
Gamma	GAMMA, WB
IRA	IRA
SR	SR, SR90, IPSA, IPS
ITH	ITH
IUS	IU
IU	IU
NP237	NP237
AM241	AM241, IPA, ITPAC, IPSA
AM243	AM243

Table 5-4. MDLs for routine processing of samples (dpm/sample unless otherwise noted).[a]

Analysis	Analysis code	Constituents reported	Urinalysis	Fecal analysis
Pu isotopic	IPU	Pu-238, Pu-239+240	0.02	0.2
Pu isotopic	IPUL	Pu-238, Pu-239+240	0.005	Not applicable
Am-241	AM241	Am-241	0.02	0.2
Am-243	AM243	Am-243	0.02	0.2
Cm isotopic	ICM	Cm-242, Cm-244	0.02	Not applicable
U isotopic	IU	U-234, U-235, U-238	0.02	Not applicable
Th isotopic	ITH	Th-228, Th-229, Th-230, Th-232	0.1	1
Np-237	NP237	Np-237	0.02	0.1
Tritium	H3	H-3	20 dpm/mL	Not applicable
Sr – total	SR	sum: Sr-89 + Sr-90	10	Not applicable
Sr-90	SR90	Sr-90	10	Not applicable
Gamma spec.	LEPD	Am-241	5	Not applicable
U-236 mass	U236	U-236	140 µg/sample	Not applicable
U-238 mass	U238	U-238	0.06 µg/sample	0.3 µg/sample
Pm-147	PM147	Pm-147	50	200

a. Use the MDAs for the individual analyses in the case of sequential analyses.

individual's radiologically controlled area entries since the most recent bioassay has been completed showing that additional bioassay was not necessary.

5.2.3 Special Bioassay

PNNL recommends special bioassay under the following circumstances, unless they are caused by radon progeny:

- Facial contamination that indicates a potential intake,
- Nasal contamination is present,
- Air monitoring indicates a potential for an intake that would result in a committed effective dose of 100 mrem or more,
- An unplanned intake is suspected for any reason, and
- Skin contamination is in excess of established thresholds for alpha or beta/gamma emitters.

Table 5-5. MDLs for priority processing of samples (dpm/sample unless otherwise noted).[a]

Analysis	Analysis code	Constituents reported	Urinalysis	Fecal analysis
Pu isotopic	IPU	Pu-238, Pu-239+240	0.02	0.2
Pu isotopic	IPUL	Pu-238, Pu-239+240	0.005	Not applicable
Cm isotopic	ICM	Cm-242, Cm-244	0.02	0.2
U isotopic	IU	U-234, U-235, U-238	0.02	0.3
Ra isotopic	IRA	Ra-224, Ra-226	0.3	1.5
Np-237	NP237	Np-237	0.02	0.1
Am-241	AM241	Am-241	0.02	0.2
Am-243	AM243	Am-243	0.02	0.2
Th isotopic	ITH	Th-228, Th-229, Th-230, Th-232	0.1	1
U-236 mass	U236	U-236	140 µg/sample	Not applicable
U-238 mass	U238	U-238	0.06 µg/sample	0.3 µg/sample
Tritium	H3	H-3	20 dpm/mL	Not applicable
C-14	C14	C-14	10 dpm/mL	200
Sr – total	SR	sum: Sr-89 + Sr-90	10	30
Sr isotopic	ISR	Sr-89, Sr-90	30	45, 30 respectively
Sr-90	SR90	Sr-90	10	30
Pm-147	PM147	Pm-147	50	200
Pu-241	PU241	Pu-241	10	10
Gamma spec.	LEPD	Am-241	5	5

a. Use the MDAs for the individual analyses in the case of sequential analyses.

Table 5-6. MDLs for expedited processing of samples (dpm/sample unless otherwise noted).[a]

Analysis	Analysis code	Constituents reported	Urinalysis	Fecal analysis
Pu isotopic	IPU	Pu-238, Pu-239+240	0.08	3
Cm isotopic	ICM	Cm-242, Cm-244	1.2	70
U isotopic	IU	U-234, U-235, U-238	0.12	4
Ra isotopic	IRA	Ra-224, Ra-226	0.3	3
Am-241	AM241	Am-241	0.08	6
Am-243	AM243	Am-243	0.08	6
Np-237	NP237	Np-237	0.02	0.1
Th isotopic	ITH	Th-228, Th-229, Th-230, Th-232	0.1	1
U-238 mass	U238	U-238	0.5 µg/sample	5 µg/sample
Tritium	H3	H-3	100 dpm/mL	100 dpm/mL
C-14	C14	C-14	20 dpm/mL	2,000
Pm-147	PM147	Pm-147	200	2,000
Sr – total	SR	sum: Sr-89 + Sr-90	50	150
Gamma spec.	LEPD	Am-241	5	5

a. Use the MDAs for the individual analyses in the case of sequential analyses.

In addition to the special bioassay drivers itemized above, PNNL workers can request bioassay.

5.3 PNNL INTERNAL MONITORING METHODS AND SENSITIVITIES

5.3.1 In Vitro Analyses

In vitro analyses for PNNL are performed by its analytical services contractor, a commercial vendor in Richland, Washington. The services include urinalysis, fecal analysis, and other nuclide-specific analyses.

Table 5-7. MDLs for emergency processing of samples (dpm/sample unless otherwise noted).

Analysis	Analysis code	Constituents reported	Urinalysis	Fecal analysis
Pu isotopic	IPU	Pu-238, Pu-239+240	0.5	9
Cm isotopic	ICM	Cm-242, Cm-244	10	240
U isotopic	IU	U-234, U-235, U-238	1	12
Ra isotopic	IRA	Ra-224, Ra-226	2	10
Am-241	AM241	Am-241	0.5	2
Am-243	AM243	Am-243	1	20
Np-237	NP237	Np-237	1	20
Th isotopic	ITH	Th-228, Th-229, Th-230, Th-232	1	10
U-238 mass	U238	U-238	7 µg/sample	8 µg/sample
Tritium	H3	H-3	100 dpm/mL	Not applicable
C-14	C14	C-14	100 dpm/mL	10,000
Pm-147	PM147	Pm-147	1,000	10,000
Sr – total	SR	sum: Sr-89 + Sr-90	80	450
Gamma spec.	LEPD	Am-241	20	20

Tritium
The tritium monitoring program is based on tritium in the oxide form because that is the typically encountered type. Tritium bioassay is performed via liquid scintillation counting of tritiated water vapor in urine. Only 1 mL is required for analysis, so samples of essentially any volume can be used. Samples are collected as single void or simulated 12-hour.

Strontium
Samples are counted using a gas proportional counter after chemical processing. Separation chemistry for yttrium is performed if ^{90}Sr identification is desired.

Uranium
Urinalysis for uranium can be done on a mass basis or isotopically by alpha spectrometry. Mass-based analysis is used for DU, NU, and RU. A screening level of 0.2 µg/d is used for the upper range of the normally expected excretion rate, reflecting an occupationally attributable excretion rate of 0.18 µg/d above the geometric mean environmental level of 0.02 µg/d established for the PNNL workforce.

Simulated 24-hour samples are collected for uranium urinalysis via alpha spectrometry. Screening levels for uranium isotopic analysis are 0.16 dpm for $^{233+234}$U, 0.007 dpm for ^{235}U, and 0.15 dpm for ^{238}U. These values correspond to an excretion rate of 0.2 µg/d for NU. Values above the screening levels trigger an investigation and perhaps a dose evaluation.

Transuranic Materials
Urinalyses can be performed for plutonium, americium, neptunium, and curium. After chemical processing, appropriate tracers are used to determine the chemical yield of the process. Split samples or multiple samples are used to accommodate analyses for multiple isotopes for a given individual.

Other Radionuclides
In addition to those above, PNNL has included the following analyses in the urinalysis sensitivity requirements it specifies to its analytical services contractor:

- Radium isotopic,
- Thorium isotopic,
- ^{14}C,
- ^{147}Pm,

- ^{241}Pu, and
- Gamma spectrometry for ^{241}Am.

5.3.2 In Vivo Counting

In vivo measurements for PNNL are performed by the Hanford mission support contractor at the 747A Building. The in vivo counting systems available to PNNL through this arrangement include the following:

- Whole-body counting using a stand-up counter containing multiple sodium iodide (NaI) detectors,
- Whole-body counting or scanning using a coaxial germanium system, and
- An array of planar hyperpure germanium (HPGe) detectors that can be used in multiple configurations.

The stand-up NaI system is also known as the preview counter. For whole-body counts, PNNL has the option of requesting a screening count using the preview counter, or a 10-minute count using the coaxial germanium system.

The HPGe detectors can be used in a variety of geometries including chest counting, skull counting, liver counting, thyroid counting, lymph node counting, and wound counting.

Chest Counting
Chest counting is performed by placing an array of four planar HPGe detectors anteriorly over the individual's lungs, in light contact with the chest. Chest wall thickness correction is made based on height-to-weight ratio. Ultrasound measurement of chest wall thickness is used in cases of known depositions. Chest count measurements that have been corrected for contributions from deposition in the skeleton and, perhaps, the liver, represent lung burden assays.

A chest count result can be considered to be a conservative estimate of a lung burden except for short periods after intake. The need for correcting a chest count result for skeletal deposition is usually determined from a skull count once a lung deposition has been confirmed. Likewise, liver counts can be used to determine if a correction for liver deposition is needed. Liver counts are primarily used for long-term follow-up and to confirm deposition estimates from urinalysis (Maclellan 2013).

The Hanford chest counting system routinely reports ^{241}Am, ^{235}U, and ^{234}Th. A peak search algorithm is used to identify the presence of other gamma lines. The normal counting time is 3,000 seconds, but longer counts can be used if greater sensitivity is needed. If a radionuclide is detected, the individual is asked to shower and change into clean coveralls to be recounted. Recounts are typically 3,600 seconds in duration. The 3,000- and 3,600-second counts can then be summed, if desired, for greater sensitivity.

Uranium detection is achieved by measuring photon emissions from ^{235}U and ^{234}Th. The latter is normally assumed to be in secular equilibrium for uranium contamination at PNNL. However, this assumption is not correct if the uranium source material has been separated from its progeny elements within about 6 months. PNNL has determined that in vivo measurement of ^{234}Th and ^{235}U are roughly equal in terms of their ability to indicate intakes of RU. Thorium-234 is a more sensitive indicator for natural or DU.

Other In Vivo Counting Geometries
In addition to chest counting, the Hanford planar HPGe system is also used in the following geometries:

- Skull counts for skeletal deposition are performed by placing planar germanium detectors on the forehead. A typical count time is 3,000 seconds.

- Liver counts are performed by placing an array of HPGe detectors anteriorly over the liver. The routine counting time is 3,000 seconds. The liver counting geometry is calibrated using ^{241}Am.

- Thyroid counts are performed by placing a single HPGe detector 10 cm above the thyroid. The routine counting time is 600 seconds.

- Wound counts are performed using a single HPGe detector. The typical count time is 10 minutes. The Hanford in vivo program also has portable germanium systems for performing wound counts in field locations.

Other types of in vivo counts performed for plutonium at Hanford include lymph node counts and scanning lung counts.

5.3.3 Bioassay Measurement Sensitivities

5.3.3.1 In Vitro Analyses

PNNL specifies reporting levels to its analytical services contractor and requires the contractor to provide prompt notification in the event a routine bioassay result exceeds a specified level. Analytical requests to the contractor include one of four processing categories: routine, priority, expedited, and emergency. All results are to be promptly reported in the case of priority, expedited, or emergency analysis requests. PNNL compares the analytical results with its screening levels to determine if additional investigation or dose assessment are warranted.

Tables 5-8 to 5-10 list the contractually mandated minimum detection levels (MDLs) PNNL has established with its analytical services contractor as of April of 2013. Values are given for each of the four processing categories. These values should be used for missed dose assignments in cases in which an analysis-specific detection limit or MDA is not reported.

In addition to meeting the detection levels for gamma spectrometry analyses in Table 5-8, PNNL also requires that the analytical services contractor “resolve and quantify” gamma-emitting radionuclides in submitted urine samples at a nominal detection level of 20 dpm relative to the energy and photon abundance for ^{137}Cs. That criterion applies to routine processing for isotopes having a half-life greater than 30 days and energy greater than 100 keV. For priority processing the detection level criterion is twice the propagated uncertainty.

5.3.3.2 In Vivo Analyses

For whole-body counts, PNNL has the option of requesting a screening count using the preview counter (a stand-up NaI detector system), or a 10-minute count using the coaxial germanium system. Nominal MDA values for each system are given in Table 5-9.

Table 5-8. Contractual MDLs for processing of gamma spectroscopy samples (dpm/sample).[a]

Isotope	MDL
Co-60	35
Cs-134	20
Cs-137	20
Mn-54	20
Na-22	25
Ru-106	120

a. The MDL is in dpm/L for sample volumes ≥1 L.

Table 5-9. Nominal MDAs for the Hanford whole-body counters (nCi).

Isotope	Preview counter[a]	Coaxial germanium counter[b]
K-40	10	7
Co-60	1.2	0.8
Cs-137	1.3	1.0
Eu-154	7.0	2.0

a. Count time = 200 s.
b. Count time = 600 s.

The Hanford in vivo facility includes an array of planar HPGe detectors that can be used in a variety of geometries including chest counting, skull counting, liver counting, and thyroid counting (single detector). Nominal MDA values for these configurations are given in Table 5-10.

Table 5-10. Nominal MDA values for the Hanford planar HPGe detectors in various configurations (nCi).[a]

Geometry and isotope	MDA
Normal chest, Am-241	0.16
Normal chest, U-235	0.09
Normal chest, Th-234	1.5
Skull for skeletal burden, Am-241	0.5
Liver, Am-241	0.17
Thyroid, I-125	0.1
Thyroid, I-129	0.2
Thyroid, I-131	0.26

a. Normal chest: 3,000-s count, four detectors, avg. size subject.
Skull: 3,000-s count, two detectors on forehead.
Liver: 3,000-s count, three detectors over liver, avg. size subject.
Thyroid: 600-s measurement, one 38-cm^2 detector 10 cm above thyroid.

5.4 INTERNAL DOSIMETRY RECORDS

Before 2013, radiological exposure records and reports for PNNL workers were maintained by the Hanford mission support contractor; PNNL has managed them since then.

The primary PNNL record of internal dose is the internal dose evaluation report. These reports are issued for each assessed internal exposure and are stored in the radiation exposure files by the Radiation Protection Division.

Dose information from the internal dose evaluation report, including summary intake information, is maintained by the Radiation Protection Division in the Sentinel database. The Sentinel database also includes bioassay results and other information. The Sentinel database contains information for PNNL-monitored workers as of 2013. Before then such information is found in the Hanford REX

database, and a subset of that database known as the Internal Dose Tracking System (INTERTRAC) database.

The following tables list the definitions and meanings of various codes that might be encountered when reviewing internal dosimetry data from the Sentinel and INTERTRAC databases (Tables 5-11 to 5-26 and Tables 5-27 to 5-30, respectively).

Table 5-11. Sentinel analysis codes and reported isotopes.

Code	Isotopes
AM241	Am-241
AM243	Am-243
C14	C-14
H3	H-3
IPIU	Pu-238, Pu-239, U-234, U-235, U-238
ICA	Am-241, Cm-242, Cm-244
ICM	Cm-242, Cm-244
IPA	Pu-238, Pu-239, Am-241
IPIU	U-234, U-235, U-238, Pu-238, Pu-239
IPS	Pu-238, Pu-239, SR
IPSA	Pu-238, Pu-239, SR, Am-241
IPU	Pu-238, Pu-239
IPUB	Pu-238, Pu-239, Pu-241
IPUBA	Pu-238, Pu-239, Pu-241, Am-241
IPUL	Pu-238, Pu-239
IRA	Ra-224, Ra-226
GAMMA	See Table 5-8
ISR	Sr-89, SR-90
ITH	Th-228, Th-229, Th-230, Th-232
ITPAC	Pu-238, Pu-239, Am-241, Cm-242, Cm-244
IU	U-234, U-235, U-238
IUPU	U-238, Pu-238, Pu-239
LEPD	Am-241
NP237	Np-237
PM147	Pm-147
SR	Total Sr
SR90	SR-90
U236	U-236
U238	U-238

Table 5-12. Sentinel analytical laboratory codes.

Code	Laboratory
GL	General Engineering Laboratories (GEL Laboratories)
IT	IT Analytical Services – Richland
LA	Los Alamos National Laboratory
OR	Oak Ridge National Laboratory
PL	PNNL Analytical Chemistry Laboratory
QN	Quanterra
RE	Reynolds Electrical and Engineering Company, Nevada Test Site)
ST	Severn Trent Laboratories – Richland, Washington
TA	TMA/Norcal, Richmond, California
WH	Westinghouse Hanford Company 222-S Lab

Table 5-13. Sentinel bioassay frequency codes.

Code	Bioassay frequency
A	Annual
B	Biennial
D	Special day
F	5 yr
Q	Quarterly
S	Semiannual
M	Monthly
W	Weekly
X	Biweekly

Table 5-14. Sentinel sample type codes.

Code	Type of sample
B	Blood
F	Feces
S	Sputum
T	Tissue
U	Urine
W	In vivo

Table 5-15. Sentinel bioassay measurement reason codes.

Code	Name	Description
BL	Baseline	Measurement is performed to establish a reference level against which subsequent measurements are compared. Generally, this might be for new employees or for established employees before commencing work with radioactive materials, beginning a specific type of radiation zone work, or making an offsite trip where potential intakes could occur.
PR	Periodic	Periodic measurement is performed at a regularly scheduled interval.
EA	End of assignment	Measurement is performed after completion of specific work assignment, but not end of employment.
SP	Special	Measurement is performed as part of a specific investigation of potential internal dose. Might include response to off-normal work conditions or follow-up of abnormal periodic measurements.
CR	Contractor request	Measurement requested by employer for reasons other than periodic, baseline, end of assignment, or special investigation.
RA	Reanalysis A	First repeat in vivo measurement or second aliquot analysis of an excreta sample.
RB	Reanalysis B	Second repeat in vivo measurement or third aliquot analysis of an excreta sample.
RC	Reanalysis C	Third repeat aliquot analysis of an excreta sample.
R1	Recount 1	First recount of original excreta sample or repeat in vivo examination.
R2	Recount 2	Second recount of original excreta sample or repeat in vivo examination.
QR	Quality and research	Measurement performed as part of quality control, quality assurance, or research work.
TM	Termination	Final bioassay at termination of employment.
12	Contract work	In vivo measurement performed under contract to customers rather than for Hanford employees.
20	Source count	In vivo source count made for system calibration or as a function check, usually using a known check source.
30	Background count	In vivo system background measurement performed for system calibration or as a functional check.

Table 5-16. Sentinel bioassay sample kit codes and sample date conventions.

Kit code for delivery and retrieval	Kit code for pick-up	Media	Description
1	P	Urine	Approximate 24-hour urine collection. Collected at home over a 2-d period. Used for routine sampling and when a larger volume sample is desired. Designated sample date is the day after kit delivery to the employee.
2	Q	Urine	Approximate 12-hr urine collection for termination sampling only. Collected at home overnight. Designated sample date is the day after kit delivery to the employee.
3	R	Urine	Total 24-hr urine collection. Collected at home and at work (if necessary) to collect all urine voided during a 24-hour period. Generally used for sampling immediately after an occurrence or for work restriction sampling. Designated sample date is the day after delivery or the date on which the sample collection began.
4	S	Urine	Single void (spot urine) collection. Collection in a single bottle, used for initial indications of an intake or when small sample volumes are adequate. Designated sample date is the date of voiding.
5	T	Feces	Collection of a single fecal voiding usually for investigation of a potential intake. Sample date is the day after kit delivery or date on which the sample was voided.
6	U	Urine	Partial day or approximate 12-hr collection. Usually collected at home overnight. Used for collection after an occurrence or when a large volume urine sample is not necessary. Designated sample date is the date of delivery to the employee.
7	V	Urine	Approximate 12-hr collection Sunday-Monday sample (Friday delivery only). Generally used for workers chronically exposed to soluble uranium. Designated sample date is the Sunday in the sampling period.
8	W	Feces	Collection of a single fecal voiding used for a special program for plutonium oxide workers. Designated sample date for shift workers is the Tuesday of long shift change, and for day workers is the appropriate Sunday.
9	X	Urine	Kit designed for collection of urine outside the local service area. Transportation is handled by private carrier. Generally used for termination samples not collected locally.
A	Y	Urine	Simulated 48-hr urine collection. Collected at home over a 4-d period. Used for IPUL sampling. Designated sample date is 2 d after kit delivery to the employee.
B	Not applicable	Urine	12-hr urine collection for termination sampling only. Collected at home overnight. Kit delivered in normal manner, but brought to a designated onsite location by worker for pick-up by Contractor. Designated sample date is the day after the date of kit delivery to the employee. Delivery only, no home pick-up required.

Table 5-17. Sentinel sample status codes.

Code	Description
CN	Container not out
DL	Kit delivered
FA	Failed analysis
IS	Insufficient volume
LC	Lost container
ND	Kit not delivered
NE	Not evaluated
NS	No sample
OR	Order received by laboratory
PE	Pending (after 03/31/2005: awaiting instructions for analysis)
PN	Pending (before 04/1/2005)
RV	Valid sample received

Table 5-18. Sentinel bioassay sample processing codes.

Code	Description
R	Routine
P	Priority
X	Expedited
E	Emergency

Table 5-19. Sentinel no-sample codes.

Code	Description
CS	Cancelled sample/analysis.
CT	Sample lost due to bioassay analysis contract termination.
FA	Failed analysis. A valid analytical result could not be obtained.
IS	Insufficient sample volume.
LC	Lost container. Sample kit not retrieved.
ND	Not delivered. Sample scheduled but kit never delivered.
NE	Not evaluated. Sample was collected but not analyzed. Typically used when a backup sample was obtained but was not needed.
NS	No sample. Kit retrieved but worker did not provide a sample.

Table 5-20. Sentinel unit codes.

Code	Units
DPM/S	dpm/sample
UG/S	µg/sample
UCI/L	µCi/L
NCI	nCi
UCI	µCi/sample
DPM/ML	dpm/mL

Table 5-21. Sentinel person codes.

Code	Description
E	Employee
F	Fetus
N	Nonresident
S	Subcontractor (this code is inactive)
V	Visitor

Table 5-22. Sentinel in vivo analysis request codes.

Code	Analysis
CA	Chest count for Am-241 only
CC	Chest count for Am-241, U-235, and Th-234
CU	Chest count for U-235 and Th-234

Table 5-23. Sentinel in vivo schedule (measurement) type codes.

Code	Measurement type
C	Chest count
C2	Extended chest count
HC	Head and chest count
HD	Head count
H2	Head and extended chest count
LC	Liver and chest count
LV	Liver count
LY	Lymph node count
TC	Thyroid and chest count
TH	Thyroid count
WB	Whole-body count
WC	Whole-body count: coaxial germanium counter
WD	Wound count

Table 5-24. Sentinel in vivo detector codes.

Code	Type of detector or counting cell
CC	Coaxial germanium counter for whole-body counts
DS	Stainless Steel Room with digital signal processing
LD	Lead Room for special counting geometries
CH	Lead Room for special counts
SU	Stand-up whole-body counter
SS	Stainless Steel Room for lung count
IR	Iron Room counter for lung count

The above in vivo detector codes are those that were typically in use by the Hanford in vivo counting group as of August 2003. See the Hanford site profile for additional information on these detectors and facilities.

Table 5-25. Sentinel body location codes for in vivo counts.

Code	Body location
ABD	Abdomen
CA1	Chest – americium
CA2	Chest – americium corrected by ultrasound
CC1	Chest – combination: americium and uranium
CC2	Chest – combination: americium and uranium corrected by ultrasound
CHT	Chest result
CH1	Chest result
CH2	Chest result corrected for chest wall thickness via ultrasound
CU1	Chest – ultrasound
CU2	Chest – uranium corrected by ultrasound
HND	Hand
KNE	Knee
LG1	Lung result: chest result corrected for skeleton burden interference
LG2	Lung result: chest result corrected for skeleton and liver burden interference
LV1	Liver
LV2	Liver result corrected for skeleton burden interference
LV3	Liver result corrected for skeleton and lung burden interference
LYM	Lymph nodes
SK1	Skeleton result based on a head count
SK2	Skeleton result based on something other than a head count
SPL	Special
THX	Thorax
THY	Thyroid
TRY	Throat
WBD	Whole body
WND	Wound

Table 5-26. Sentinel in vivo no-result codes.

Code	Reason for no result
C	External contamination other than radon detected on the subject. Measurement invalid; no results obtained.
F	Failure of equipment or faulty setup of equipment. Measurement invalid; no results obtained.
I	Interference from localized activity in another part of the subject's body. Measurement invalid; no results obtained.
L	Location of internal or external activity was qualitatively determined by mapping, masking, or collimating. May include one or more measurement counts. These measurements are qualitative for identifying location of activity and do not yield quantifiable estimates of activity.
M	Medically administered radioactivity interfered with measurement. Measurement invalid; no results obtained.
N	No show. Worker did not meet appointment.
P	Preliminary count, when followed by a more accurate record count. Used to indicate measurement taken, but not a record count.
R	Radon interference from subject's clothing, hair, or skin. Measurement invalid; no results obtained.
S	The subject's actions interrupted completion of the count. Measurement invalid; no results obtained.
W	Waived. Scheduled exam was waived based on needs review.
X	Measurement invalid; no results obtained. Other no-result codes do not apply. See comment field for a brief description.
Z	Test case.

Table 5-27. INTERTRAC mode of intake codes.

Code	Mode of intake
ABS	Absorption
ING	Ingestion
INH	Inhalation
NON	None (no intake)
UNK	Unknown
WND	Wound

Table 5-28. INTERTRAC evaluation reason codes.

Code	Reason for evaluation
A	Annual chronic intake evaluation
C	Contractor requested evaluation
D	DAC-hours evaluation
H	High routine bioassay evaluation
I	Incident evaluation
N	New hire measurement or previous employment record indicated exposure before Hanford employment
R	Reevaluation

Table 5-29. INTERTRAC source of intake codes.

Code	Source of intake
DHE	Intake at DOE site while employed at Hanford
HAN	Intake at Hanford
NHE	Intake at non-DOE site while employed at Hanford
NOC	Nonoccupational intake
PTH	Intake occurred before Hanford employment

Table 5-30. INTERTRAC miscellaneous codes.

Code Type	Code	Description
Intake confirmed	Y	Yes (occupational intake)
Intake confirmed	N	No
Nature of intake	A	Acute
Nature of intake	C	Chronic
Recorded dose	Y	Yes (occupational intake)
Recorded dose	N	No
Recorded dose	O	Undetermined: old evaluation assessing body burden rather than dose, or an evaluation in process
Recorded dose	Z	Recorded dose is zero mrem
Source known	Y	Yes
Source known	N	No
Type of evaluation	P	Preliminary
Type of evaluation	F	Final

6.0 OCCUPATIONAL EXTERNAL DOSE

6.1 INTRODUCTION

6.1.1 Purpose

The purpose of this section is to detail historical external dosimetry programs, systems, and practices at PNNL. This information may be used by dose reconstructors as needed to evaluate external occupational doses for EEOICPA claimants.

6.1.2 Scope

This section describes PNNL external monitoring practices as of January 2013. Before then a common external monitoring program was in place for both PNNL and Hanford. Information about external monitoring at PNNL during 2005 through 2012 should therefore be obtained from the Hanford site profile.

6.2 BACKGROUND

Before 2012, PNNL or one of its predecessors had provided dosimetry services for both Hanford and PNNL since Hanford's beginning in the early 1940s. A single DOELAP accreditation had been maintained for external dosimetry at both sites since the DOELAP program began in the late 1980s. This arrangement continued until October 1, 2012, when the responsibility for radiation dosimetry services for Hanford transferred from PNNL to the mission support contractor for the Hanford site. At that time PNNL began maintaining its own DOELAP accreditation and providing external dosimetry services to PNNL, the DOE Pacific Northwest Site Office, and their subcontractors. The PNNL DOELAP accreditation is sponsored by this office (Rathbone 2012).

Between October 1, 2012, and January 1, 2013, PNNL purchased dosimetry services from the Hanford mission support contractor. PNNL began using its own commercial vendor for external monitoring on January 1, 2013. The PNNL external dosimetry program is asserted to comply with DOE requirements in 10 CFR Part 835 and DOE Standard 1095-2011 for DOELAP (DOE 2011) as well as guidance in DOE G 441.1-1C, *Radiation Protection Programs Guide* (Rathbone 2012).

6.2 DOSE RECONSTRUCTION PARAMETERS

6.2.1 Administrative Practices

The PNNL radiation control program requires that personnel dosimeters be provided to and used by the following groups (BMI 2013b, Article 511.1):

- Radiological workers who, under typical conditions, are likely to receive one or more of the following:
  - An effective dose to the whole body of 100 mrem or more in a year,
  - An equivalent dose to the skin or to any extremity of 5 rem or more in a year, or
  - An equivalent dose to the lens of the eye of 1.5 rem or more in a year.
- Declared pregnant workers who are likely to receive from external sources an equivalent dose to the embryo/fetus in excess of 10% of the applicable limit at 10 CFR 835.206(a).
- Occupationally exposed minors likely to receive a dose in excess of 50% of the applicable limits at 10 CFR 835.207 in a year from external sources.

- Members of the public entering a controlled area likely to receive a dose in excess of 50% of the limit at 10 CFR 835.208 in a year from external sources.

- Individuals entering a high or very high radiation area.

In addition, the PNNL radiation control program requires that neutron dosimetry be provided if any of the above dose criteria are likely to be exceeded from neutron exposure. Further, the program manual states that DOELAP-accredited neutron dosimetry should be used whenever an individual is likely to meet or exceed the applicable dose criteria and 10% or more of the dose is likely to be from neutron exposure (BMI 2013b, Article 511.2).

Article 512 of the PNNL radiation control program requires that external dose monitoring programs implemented to demonstrate compliance with 10 CFR 835.402(a) shall be adequate to demonstrate compliance with the dose limits established in Subpart C of 10 CFR Part 835 and shall be either accredited, or excepted from accreditation, in accordance with the DOE Laboratory Accreditation Program for Personnel Dosimetry; or determined by the Secretarial Officer responsible for environment, safety and health matters to have performance substantially equivalent to that of programs accredited under the DOE Laboratory Accreditation Program for Personnel Dosimetry.

In general, PNNL does not engage in radiological operations that have a potential for significant external dose. Even with the Hanford 300 Area are included, over 80% of external dose results for PNNL workers are zero (i.e. are less than the reporting level). PNNL maintains an area dosimetry program to demonstrate that external doses to individuals working in radiological buffer areas or other areas where personnel dosimetry is not required do not exceed an effective dose of 50 mrem annually (see Section 2.4.2).

Transit Dosimeters
PNNL maintains a manual reader system for its dosimeters that it uses to evaluate transit dosimeters included in shipments from its dosimetry vendor. The onsite manual reader can also be used to read personnel dosimeters in cases when an individual might be nearing an administrative dose limit (Rathbone 2012).

6.2.2 Site Dosimetry Technology

6.2.2.1 Whole-Body Dosimeters

PNNL uses an external vendor (Landauer) for its personnel monitoring program. Two Landauer dosimeters are used:

- The InLight Model 2 (for electrons and photons), and
- The InLight Model 2T (for electrons, photons, and neutrons).

The InLight Model 2 and Model 2T are identical except the latter includes a CR-39 track-etch neutron detector. Both designs use optically stimulated luminescence, which is nondestructive, meaning a dosimeter can be reread or read on an interim basis without significantly altering the final result.

The InLight dosimeters use Al_2O_3:C as the phosphor. Al_2O_3:C is not tissue-equivalent and significantly overresponds (relative to soft tissue) at photon energies less than 100 keV. Element filters and a dose calculation algorithm are therefore used to obtain accurate results. Each dosimeter contains four elements filtered by plastic, copper, or aluminum. There is also an open window with minimal filtration. Table 6-1 gives the filter thicknesses from the front and the rear for each of the four dosimeter elements (Rathbone 2012).

Table 6-1. Front and rear filtration thickness for the InLight Model 2 and Model 2T dosimeter elements (mg/cm^2).

Aspect	Open window	Plastic	Aluminum	Copper
Front	30	298	398	568
Rear	16	284	384	554

In addition to the same four elements of the InLight Model 2 dosimeter, the Model 2T version also contains a Landauer Neutrak 144 CR-39 detector capable of measuring neutron dose from both fast and thermal neutrons. The CR-39 detector is a plastic foil made of poly-allyl diglycol carbonate ($C_{12}H_{18}O_7$). This material is commonly called CR-39, which is a trade name given to it by one of the original manufacturers. Fast neutrons are detected in CR-39 by recording tracks of recoil protons from (n,p) reactions. Thermal neutrons are detected through (n,α) reactions in a boron-loaded Teflon filter (also called a radiator) that covers part of the CR-39 chip. The other part of the chip is covered by a polyethylene filter. The area behind the polyethylene filter is sensitive to fast neutrons in the energy range from 40 keV to 40 MeV. The area behind the boron-loaded Teflon filter responds to both fast neutrons and thermal neutrons in the energy range from 0.25 eV to 40 eV (Rathbone 2012).

The CR-39 neutron dosimeter in the InLight Model 2T dosimeter has a useful measurement range of 20 mrem to 25 rem for fast neutrons and 10 mrem to 5 rem for thermal neutrons (Rathbone 2012).

The InLight Model 2 and Model 2T are capable of detecting photons (X and gamma rays) with energies between 5 keV and 20 MeV, with a useful measurement range from 5 mrem to 1,000 rem. The InLight Model 2 and Model 2T are capable of detecting beta particles with energies greater than 150 keV (average) with a useful measurement range from 20 mrem to 1,000 rem.

There is limited potential for neutron exposures at PNNL. Sources of Cf-252 are known to have been stored in safes in Room 1344 in the EMSL and Room 1303 in Building 3440. The PNNL area dosimetry program included neutron monitoring in those areas to show any neutron dose received by unmonitored personnel was less than 50 mrem per year. There could be some potential for neutron generation associated with accelerator operations depending on the particles and energies involved. PNNL's criteria for neutron monitoring are discussed in Section 6.2.1. In addition to the other criteria for personnel external monitoring, neutron monitoring is recommended whenever 10% or more of an individual's dose is likely to be from neutron exposure.

6.2.2.2 Extremity Dosimetry

PNNL issues extremity dosimetry to individuals who are likely to be exposed to nonuniform radiation fields where the shallow dose to the extremities is likely to significantly exceed the shallow dose to the whole body. The PNNL extremity dosimeters are calibrated to measure *Hp(0.07)* when worn on the finger.

PNNL uses the Landauer U-Ring dosimeter. It contains a single Harshaw TLD-100 (LiF) chip in a polystyrene cap that provides a density thickness of 40 mg/cm^2. The useful range for the U-Ring dosimeter is considered to be 30 mrem to 500 rem shallow dose equivalent (SDE) (Rathbone 2012).

6.3 DOSE CALCULATION AND REPORTING

6.3.1 Dose Algorithm

The dose algorithm used with the InLight Model 2 whole-body dosimeter was designed to measure total personal dose equivalent at depths of 7,300 and 1,000 mg/cm^2 from radiation fields including photons from 20 keV to over 6 MeV and high and low energy beta radiations. Additionally, the

algorithm is capable of accurate assessment of mixed fields including mixtures of the photons or photons and betas from the above fields. The dose algorithm was based upon correction factors derived from the American National Standard HPS N13.11-2001 (HPS 2001) which incorporates the standard beams listed in ISO 4037-4:2004 (ISO 2004).

6.3.2 Exposure Energy Spectra

Dose reconstruction under the NIOSH program requires estimates of exposure percentages within specific energy bands for each type of radiation as follows (NIOSH 2007):

- Photons:
  - <30 keV,
  - 30–250 keV, and
  - >250 keV;
- Beta particles:
  - <15 keV, and
  - >15 keV;
- Neutrons:
  - <10 keV,
  - 10–100 keV,
  - 100 keV–2 MeV,
  - 2–20 MeV, and
  - >20 MeV.

For external exposures, betas with energies of less than 15 keV are not applicable. Otherwise, the energy spectrum choices that are most favorable to the claimant should be used when performing organ dose conversion from reported external dosimetry results from PNNL unless other, exposure-specific spectral information is available. For photon exposures, the 30 – 250 keV energy range is typically the most favorable to the claimant for likely noncompensable claims (i.e. when maximizing assumptions are desired). For likely compensable claims (minimizing assumptions) a photon energy split of 25% less than 30 keV photons and 75% greater than 250 keV photons should be used. For neutron exposures, the 0.1 – 2 MeV energy range is typically the most favorable to the claimant (ORAUT 2006).

There is an exception to the above favorable to the claimant photon energy group selections for cases involving dose to the skin from work with or near isotopes of plutonium. In that case, since the dose conversion factor for the skin is considered to be 1.0 for all energies, one should select the less than 30 keV photon energy group given the higher risk factor for that group relative to the 30 – 250 keV group in the Interactive RadioEpidemiological Program (ORAUT 2006).

The dosimetry results reported by Landauer are in units of personal dose equivalent and already reflect current values for the applicable radiation and tissue weighting factors. Hence, beginning in 2013 when PNNL adopted its own external dosimetry program, no adjustment should be needed before converting the reported results to organ dose. The external dosimetry program at use at PNNL (which was the same as the Hanford program prior to 2013) adopted the neutron radiation weighting factors from ICRP 60 as of 2011 (ORAUT 2011). For neutron results reported prior to 2011, corrections should be applied for any differences between the neutron radiation weighting factors (or

quality factors) used by the Hanford program and those from ICRP 60, as discussed in the Hanford site profile or other, applicable project guidance.

6.3.3 Missed Dose

Lower limit of detection (LLD) data for the InLight Model 2T dosimeter are presented in Table 6-2 for exchange periods of 45, 75, and 100 days. The data were calculated from DOELAP testing results for low-energy photon, high-energy photon, general beta particle, DU beta, and unmoderated neutron fields.

Table 6-2. LLD values for the InLight Model 2T dosimeter (mrem).[a]

Irradiation category	45-d SDE	45-d DDE	45-d neutron	75-d SDE	75-d DDE	75-d neutron	100-d SDE	100-d DDE	100-d neutron
Low-energy photon	11	9	N/A	18	17	N/A	21	17	N/A
High-energy photon	8	8	N/A	13	14	N/A	16	14	N/A
Beta – general	13	N/A	N/A	22	N/A	N/A	25	N/A	N/A
Beta – DU	13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Unmoderated neutron	N/A	N/A	13	N/A	N/A	11	N/A	N/A	17

a. N/A = not applicable.

Landauer's reporting levels for dose results from the InLight Model 2T dosimeter are:

- SDE, 5 mrem;
- Deep dose equivalent (DDE), 5 mrem;
- DDE from fast neutrons, 20 mrem; and
- DDE from thermal neutrons, 10 mrem.

For photon and beta exposures it is anticipated that the LLD value that is most favorable to the claimant should be selected in most cases. For SDE this value is 25 mrem. For DDE it is 17 mrem.

The LLD values for neutron exposures in Table 6-2 are below the reporting level of 20 mrem DDE for fast neutrons, so 20 mrem should be used as the LLD for fast neutron exposures.

Landauer's reporting level for the U-Ring extremity dosimeter is 30 mrem. This value is greater than the accepted value for the LLD for this dosimeter and should therefore be applied as the LLD when needed.

Reporting levels given on dosimetry reports take precedence over the values given in this site profile.

PNNL uses a combination of monthly, quarterly, or annual dosimeter exchange frequencies depending on the expected dose. Supplemental dosimetry is used to track dose between primary dosimeter reads. The actual exchange frequency or frequencies need to be ascertained from claim records (i.e. from the monitoring period given on the dosimetry reports).

7.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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GLOSSARY

absorption type
Categories for materials according to their rates of absorption from the respiratory tract to the blood, which replaced the earlier inhalation clearance classes. Defined by the International Commission on Radiological Protection, the absorption types are F: deposited materials that are readily absorbed into blood from the respiratory tract (fast solubilization), M: deposited materials that have intermediate rates of absorption into blood from the respiratory tract (moderate rate of solubilization), and S: deposited materials that are relatively insoluble in the respiratory tract (slow solubilization).

air sampling
Collection of samples of the ambient atmosphere to detect or measure the presence of radioactive material in the air.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

bioassay
Measurement of amount or concentration of radionuclide material in the body (in vivo measurement) or in biological material excreted or removed from the body (in vitro measurement) and analyzed for purposes of estimating the quantity of radioactive material in the body. Also called radiobioassay.

depleted uranium (DU)
Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium.

derived air concentration (DAC)
Annual limit of intake of a radionuclide divided by the volume of air inhaled by Reference Man in a working year (2.4×10^3 cubic meters). A DAC-hour is the exposure to a person breathing the DAC for 1 hour.

dose reconstruction
Process of analyzing the available information including evaluation of historical methods and data to estimate the dose a person could have received from one or more radiation exposures.

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual.

dosimetry
Measurement and calculation of internal and external radiation doses.

effluent
Liquid or gaseous waste released to the environment.

element
One of the known chemical substances in which the atoms have the same number of protons. Elements cannot be broken down further without changing their chemical properties. Chemical symbols for the elements consist of either a single letter or a combination of letters,

some of which descend from the Latin names [e.g., Au from *aurum* (gold), Fe from *ferrum* (iron)]. This glossary indicates *elements* by their names. Specific *isotopes* appear as their standard chemical symbols with the number of protons and neutrons in the nucleus. For example, the isotope of uranium that contains 92 protons and 143 neutrons can appear as ^{235}U, *U-235*, or *uranium-235*. See *periodic table of the elements* and *radioactive isotope*.

enriched uranium (EU)

Uranium in which processing has increased the proportion of ^{235}U to ^{238}U to above the natural level of 0.7% by mass. Reactor-grade uranium is usually about 3.5% ^{235}U; weapons-grade uranium contains greater than 90% ^{235}U.

enrichment

Isotopic separation process that increases the percentage of a radionuclide in a given amount of material above natural levels. For uranium, enrichment increases the amount of ^{235}U in relation to ^{238}U. Along with the enriched uranium, this process results in uranium depleted in ^{235}U. See *depleted uranium*, *enriched uranium*, and *tails*.

external dose

Dose received from radiation emitted by sources outside the body.

fissionable

Capable of undergoing fission by capturing neutrons, including fast neutrons. Uranium-238 is fissionable. Fissionable indicates both spontaneous and induced fission.

geometric mean (GM)

The *n*th root of the product of all the members of a set of positive numbers, where *n* is the number of members. The sample geometric mean is designed for averaging ratio or proportion data. It is equivalent to taking logarithms of the sample values (i.e., transforming the sample), finding the arithmetic mean of the logs, and then retransforming back to the original scale (by taking antilogs). It can only be used when all the sample values are greater than zero.

glovebox

Enclosure with special rubber gloves through which an operator can handle radioactive or toxic material without risk of injury or contamination, normally operated at a slightly reduced pressure so that air leakage, if any, is inward.

high-efficiency particulate air (HEPA) filter

Dense filter that removes contaminants from air flows before return to the working environment or discharge to the outside air (exhaust).

highly enriched uranium (HEU)

Uranium enriched to at least 20% ^{235}U for use as fissile material in nuclear weapons components and some reactor fuels. Also called high-enriched uranium.

in vitro bioassay

Measurements to determine the presence of or to estimate the amount of radioactive material in the excreta or in other biological materials removed from the body.

in vivo bioassay

Measurements of radioactive material in the human body using instrumentation that detects radiation emitted from the radioactive material in the body.

internal dose
Dose received from radioactive material in the body.

isotope
One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U). Isotopes have very nearly the same chemical properties. See *element*.

lower limit of detection (LLD)
See *minimum detectable activity*.

mass spectrometer
Instrument that determines the relative concentrations of elements or molecules of various masses through electromagnetic separation of ions (spectrometry).

minimum detectable activity (MDA)
Smallest amount (activity or mass) of an analyte in a sample that can be detected with a probability β of nondetection (Type II error) while accepting a probability α of erroneously deciding that a positive (nonzero) quantity of analyte is present in an appropriate blank sample (Type I error). See *action level*, *decision level*, and *minimum reporting level*.

neutron (n)
Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen. See *element*.

nuclide
Stable or unstable isotope of any element. Nuclide relates to the atomic mass, which is the sum of the number of protons and neutrons in the nucleus of an atom. A radionuclide is an unstable nuclide.

periodic table of the elements
Arrangement of the chemical elements in order of increasing atomic number from left to right and by similar chemical properties vertically. Elements of similar properties occur one under the other, which yields groups or families of elements.

photon
Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

progeny
Nuclides that result from decay of other nuclides. Also called decay products and formerly called daughter products. See *parent*.

radiation
Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer. See *ionizing radiation*.

radioactive
Of, caused by, or exhibiting radioactivity.

radioactive isotope
Natural or synthetic form of an atom that emits radioactivity when it decays. See *isotope*.

radionuclide

Radioactive nuclide. See *radioactive* and *nuclide*.

recycled uranium (RU)

Uranium first irradiated in a reactor then recovered through chemical separation and purification. RU contains minor amounts of transuranic material (e.g., plutonium and neptunium) and fission products (e.g., technetium) or uranium products (e.g., ^{236}U) after purification.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

sealed source

Radioactive material encased in a capsule designed to prevent leakage or escape of the material.

transuranic elements

Elements with atomic numbers above 92 (uranium). Examples include plutonium and americium.

tritium (hydrogen-3, ^{3}H, T)

Radioactive isotope of hydrogen that contains one proton and two neutrons in its nucleus. It decays by beta emission and has a radioactive half-life of about 12.5 years.

vitrification

Incorporation of radioactive waste products, particularly from nuclear fuel reprocessing, into glass. Also called glassification.