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PNNL Dose-per-Unit-Release Factors for Calculating Radionuclide Emissions Potential-to-Emit Doses

PNNL-Richland and PNNL-Sequim Campuses

August 2025

SF Snyder
TR Hay
JM Barnett

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Change History

Revision Number	Effective Date	Description of Change
0	September 2008	Initial document
1	June 2009	[co-issued as CRL-TECH-ESH-007, Rev1] This is a major rewrite therefore no revision bars are shown. Changes in this revision incorporate comments provided by WDOH and EPA and segregates unit dose factors for radioisotopes found in CAP88V3 and those for which a surrogate is derived.
2	March 2010	[co-issued as CRL-TECH-ESH-007, Rev2] Minor editorial revision was made to delete references to specific buildings on the PNNL Site, such that this technical basis document may be used in developing notice of construction applications for any building on the PNNL Site. In introduction deleted paragraph that referenced specific building.
3	December 2015	This is a significant rewrite; therefore, no revision bars are shown. Unit-release dose factors use the most current version of CAP88-PC (Version 4.0.1.17). Updated meteorological data used. PNNL Campus boundary applied rather than the PNNL Site boundary. CAP88-PCV4 has limited site-specific input ability compared to V3; therefore, default intake and exposure rates are applied. A large set of nuclides are available in CAP88-PC Version 4.0.1.17. Location Modification Factor calculations for RTL and LSL-II facilities are included within this document.
4	July 2016	This revision uses CAP88-PC (Version 4.0.1.17) with a 100-year build-up factor, updating the 50-year factor used in revision 3. The build-up factor assumes continuous facility operations with the same emission rate for the indicated number of years. The calculated Maximum Public Receptor dose factor then indicates the estimated dose for the final build-up year. Also, this revision includes a full set of unit-release dose factors for the “Maximum Air” location, the highest offsite air concentration site, regardless of occupancy at that location. Location Modification Factors for RTL and LSL-II facilities are included for both receptor types. The discussion of the Location Modification Factor was expanded, as well, for clarification. No revision bars are shown.
5	August 2025	This revision uses CAP88-PC (Version 4.1.1) for PNNL-Richland Campus dispersion and dose modeling. The updated MPR and MA receptor unit dose factors use this more recent software version and meteorology. RTL and LSL-II facilities are no longer radioactive air effluent sources, so no Location Modification Factors (LMFs) are now needed and the LMF discussion has been updated. New radioactive materials are included due to the current authorized nuclide emissions list and the need for surrogate nuclides. The current site nomenclature identifies the PNNL Campus as the PNNL-Richland campus. This revision also includes a new section for PNNL-Sequim campus PTE dose factors, using COMPLY (Version 1.7.1) dispersion and dose modeling.

Summary

This document revision reports the dose-per-unit release factors from those based on the U.S. Environmental Protection Agency code CAP88-PC Version 4.1.1. Surrogate nuclides, necessary because all radioisotopes used at Pacific Northwest National Laboratory (PNNL) are not included within CAP88-PC v4.1.1, were approved for use for dose modeling. For the first time, this revision includes potential-to-emit modeling of the PNNL-Sequim campus modeled with COMPLY Version 1.7.1.

Dose factors for relevant receptors are included. Dispersion modeling in this revision uses more recent average meteorology files. For purposes of Notice of Construction applications, both the Maximum Public Receptor and the maximum offsite air concentration dose values are presented, where the Maximum Public Receptor dose value is used to determine compliance with the maximally exposed individual limits and constraints, and the maximum offsite air location dose is provided for completeness of the application. Due to the very low levels of emissions at the PNNL-Sequim campus, only Maximum Public Receptor dose factors are provided. Dose factors tabulated here are entered into the Radioactive Material Tracking database for administrative management of campus radioactive air emissions.

For operational flexibility, a calculational approach that uses Location Modification Factors is presented. This approach would be used if a PNNL-Richland campus facility, remote from current facilities with radiological operations, began minor radiological operations prior to a revision of this document and would allow the determination of potential-to-emit doses under a simplified approach.

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
CAP-88	Clean Air Act Assessment Package–1988
CAP88-PC	Clean Air Act Assessment Package 1988–Personal Computer
CFR	Code of Federal Regulations
+D	plus decay chain products for dosimetric calculations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ERT	(PNNL) Environmental Radiation Task
HEPA	high-efficiency particulate air (filter)
LMF	Location Modification Factor
LP	Low-PTE (facility)
LSB	Laboratory Support Building
MA	maximum air
MEI	Maximally Exposed Individual
MPR	Maximum Public Receptor
NDA	nondestructive assay
NESHAP	National Emission Standards for Hazardous Air Pollutants
NOC	Notice of Construction
PNNL	Pacific Northwest National Laboratory
PSF	Physical Sciences Facilities
PTE	potential-to-emit
QA	quality assurance
RMT	Radioactive Material Tracking
WAC	Washington Administrative Code
WDOH	Washington State Department of Health

Definitions

Acute Release—A short-duration release of a radioactive air pollutant with a potentially significant dose consequence.

Aerodynamic Equivalent Diameter—The diameter of a sphere, with a density of 1 g cm^{-3}, that has the same terminal settling velocity under gravity as the airborne particle considered. Typically, a particle of arbitrary shape and density is modeled with the same aerodynamic diameter as that of a spherical water droplet having the same sedimentation velocity in quiescent air as the arbitrary particle under consideration.

Chronic Release—The nearly continuous release of small quantities of radioactive air pollutants from an emission unit over a period of at least 3 months.

Emission Unit—Any stationary source (e.g., a stack or vent) that emits or has the potential-to-emit regulated radioactive air pollutants. This may be a point source, non-point source, or source of diffuse or fugitive emissions.

Maximum Air (MA) location—A location where a facility radioactive air emission is modeled to have the greatest offsite air concentration. Higher concentrations of a given radioisotope will result in a higher receptor dose estimate. No reside/abide criteria need to be met for this location, but is assumed for the calculation of dose. The MA dose calculation is prospective in nature and uses long-term meteorological data applicable to the emission facility location.

Maximally Exposed Individual (MEI)—A hypothetical member of the public residing near the PNNL-Richland campus who, by virtue of location and living habits, could receive the highest potential radiation dose from radioactive effluents released from the PNNL-Richland campus during a past calendar year. The MEI dose calculation is retrospective in nature and uses actual emissions and meteorological data applicable to the year for which the evaluation is performed. Emissions affecting the MEI may originate from point sources (i.e., actively ventilated stacks and vents) as well as from fugitive and diffuse sources. Compliance with federal and state dose standards is determined by the MEI dose.

Maximum Public Receptor (MPR)—A hypothetical member of the public located near the PNNL-Richland campus who, by virtue of location and living habits, could receive the highest radiation dose from potential radionuclide emissions that may be released from a single emission source being considered for permitting purposes. The MPR dose calculation is prospective in nature and uses estimated potential radionuclide emissions from a proposed new or modified emission unit and long-term meteorological data applicable to the facility location.

Potential-to-Emit (PTE)—Radionuclide emissions estimated for purposes of permitting a new or modified emission unit. As defined in WAC 246-247-030(21), “the rate of release of radionuclides from an emission unit based on the actual or potential discharge of the effluent stream that would result if all abatement control equipment did not exist, but operations are otherwise normal.”

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1.0 Introduction

U.S. Department of Energy (DOE) facilities are required to demonstrate compliance with the Clean Air Act National Emission Standards for Hazardous Air Pollutants (NESHAP) for radionuclides, as published in the 1989 amendments to Title 40 Code of Federal Regulations (CFR) Part 61, Subpart H, "National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities" (40 CFR Part 61, Subpart H).

The Washington State Department of Health (WDOH) established regulations, corresponding to the federal regulations for radionuclide air emissions, in the Washington Administrative Code (WAC) Chapter 246-247, "Radiation Protection -- Air Emissions". Additional Washington State Department of Ecology regulations are found in WAC 173-480, "Ambient Air Quality Standards and Emission Limits for Radionuclides". The WDOH is responsible for implementing and enforcing regulations relating to radiological air quality in Washington State.

Regulatory requirements for determining compliance with the radionuclide air emissions standards are specified by the U.S. Environmental Protection Agency (EPA) in 40 CFR Part 61, Subpart H, Section 61.93(a), which includes:

> EPA-approved sampling procedures, computer models CAP-88 or AIRDOS-PC, or other procedures for which EPA has granted prior approval. DOE facilities for which the maximally exposed individual lives within 3 kilometers of all sources of emissions in the facility, may use EPA's COMPLY model and associated procedures for determining dose for purposes of compliance.

In WAC 246-247-035(1), the WAC adopts by reference the approved methods specified in 40 CFR Part 61, Subpart H. EPA authorized the use of the Clean Air Act Assessment Package 1988–Personal Computer (CAP88-PC) Version 4.1 software package (EPA 2020) in 2020 (Federal Register 2020-04546 [85 FR 12917] March 5, 2020, p 12917-12920).

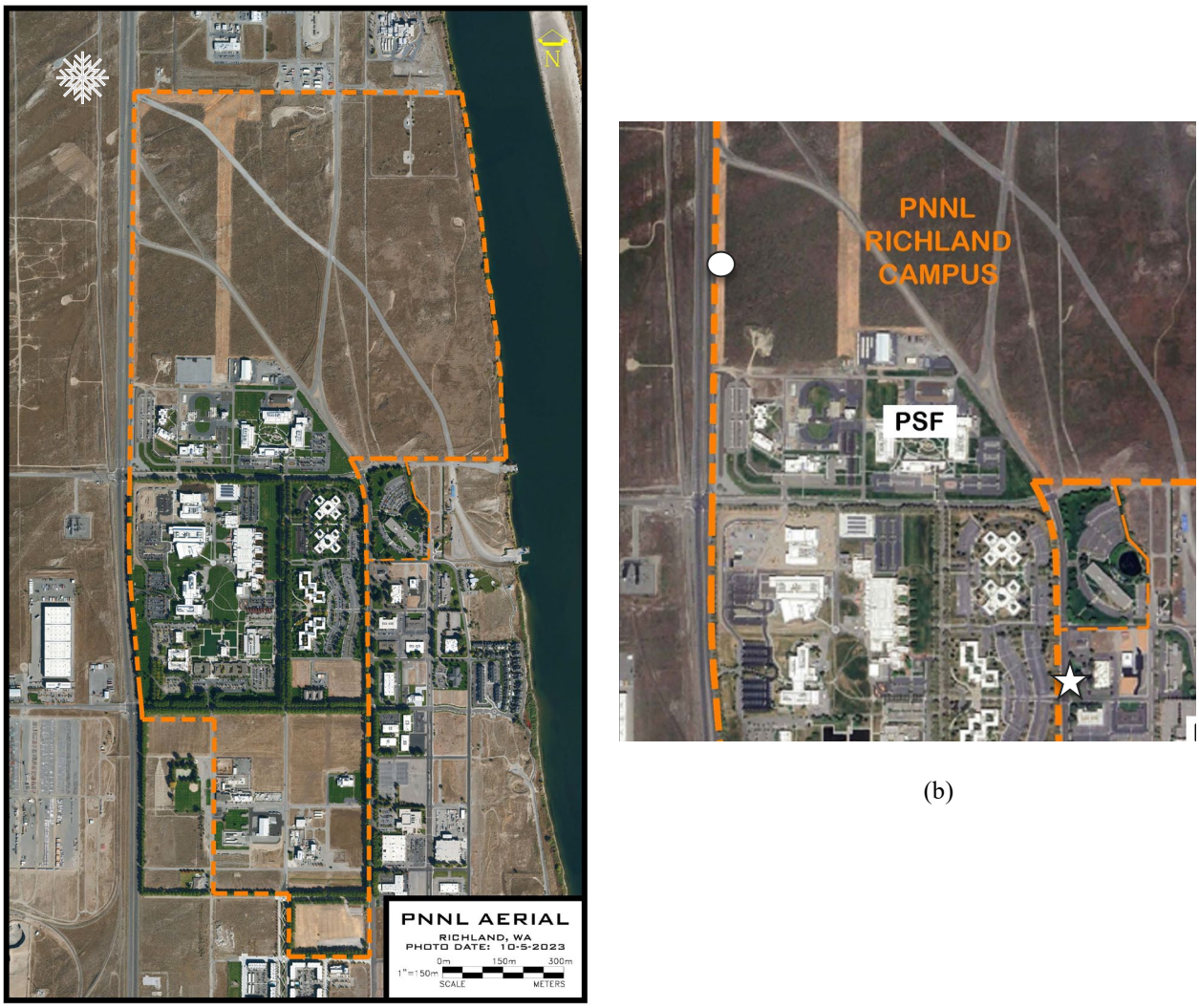
This report documents assumptions and inputs used by the PNNL Environmental Radiation Task (ERT) staff to prepare the dose-per-unit-release factors for emissions units permitted to DOE at the Pacific Northwest National Laboratory (PNNL)-Richland campus (see Section 3.0). These were calculated using the CAP88-PC Version 4.1.1 software package. This report also documents assumptions and inputs used to prepare the dose-per-unit-release factors for the single emissions unit permitted to DOE at the PNNL-Sequim campus, using the COMPLY Version 1.7.1 software package. The less complex software was used for the PNNL-Sequim campus modeling because radiological operations and emissions are significantly reduced at this facility compared to the Richland campus.

The Maximum Public Receptor (MPR) dose-per-unit-release factors are used to prepare potential-to-emit (PTE) dose estimates for an MPR in support of Radioactive Air Pollutants Notice of Construction (NOC) applications for facilities on each PNNL campus. This is implemented using PNNL's Radioactive Material Tracking (RMT) software. The dose standard is based on the dose to standard man (40 CFR Part 61, Subpart H, Sections 61.91 and 61.92), an adult; therefore, dose-per-unit-release factors presented here are those for an adult. When appropriate, radioactive air pollutants NOC applications for all new or modified emissions units are prepared in accordance with WAC 246-247 and submitted to WDOH for review and approval.

PNNL campus buildings have permitted point source or fugitive emissions units. Figure 1.1(a) shows the PNNL-Richland campus and facilities with currently permitted emissions units. Figure 1.2 shows the extent of the PNNL-Sequim campus site-wide permitted emission unit. Each campus boundary reflects its current configuration, as shown in the figures. PTE dose estimates are also useful for program planning and compliance estimations as new research activities are proposed.

With all directions of dispersion considered, the PNNL-Richland campus MPR location may be any offsite location that is currently developed and occupied. While the Laboratory Support Building (LSB) property, located SE of the Physical Sciences Facilities (PSF), is not formally part of the PNNL-Richland campus, PNNL staff manage access controls to this property; therefore, the LSB property is considered onsite for MPR determination. Other PNNL-occupied properties (e.g., Sigma 1) are similarly treated like the LSB on a case-by-case basis for compliance purposes. Also considered was a land conveyance that opened up land for development west and northwest of the PNNL boundary in late 2015. No facilities currently occupy this region. The MPR location determination (Figure 1.1, star) indicates the developed site of greatest potential dose impact, SSE of PSF.

Maximum air (MA) dose-per-unit-release factors are also provided for the PNNL-Richland campus. The MA dose-per-unit-release factors are used to estimate a dose for a hypothetical fulltime receptor at the offsite location (Figure 1.1(b), circle) indicated to have the greatest air concentration of emissions, regardless of whether that location is routinely occupied. The location, NW of PSF on Stevens Drive at the location of the PNL-1 ambient air monitoring station, is based on CAP88-PC modeling and average meteorology. Due to limited radiological operations at the PNNL-Sequim campus, only MPR (no MA dose per unit-release dose factors) are provided in this document.



(a)

(b)

Figure 1.1. (a) PNNL-Richland campus Boundary (dashed lines) with (b) Campus MPR (star) and MA (circle) Locations Identified. Snowflake symbol in (a) indicates tower providing meteorological information.

(a)

(b)

Figure 1.2. (a) PNNL-Sequim Campus Boundary (pink and blue lines). (b) Central Campus release location and MPR location.

2.0 Estimating Potential Emissions

This section describes methods outlined in WAC 246-247. WDOH and EPA Region 10 both accept 40 CFR Part 61, Appendix D, for estimating potential airborne radionuclide emissions; other approaches, including those identified herein, require regulatory approval prior to being implemented. Potential radionuclide emissions from new or modified emission units are used to determine emission monitoring requirements and other operating parameters for the emission unit. In determining potential emissions, also referred to as PTE, the emission rates are estimated assuming normal operations, but in the absence of emission-abatement and control equipment.

2.1 Approved Methods

WAC Chapter 246-247-30(21) provides the following methods to determine the PTE:

1. Multiply the annual possession quantity of each radionuclide by the release fraction for that radionuclide. Release fractions are provided in WAC 246-247-030(21)(a); they are the same as those specified in 40 CFR Part 61, Appendix D.
2. Perform a back-calculation using measured emission rates and *in situ* measurements of the control-equipment efficiencies.
3. Measure the quantities of radionuclides captured in each control device, coupled with *in situ* measurements of the control equipment efficiencies.
4. Sample the effluent upstream from all control devices.
5. Use an alternative method approved by WDOH. Under this method (WAC 246-247-030(21)(e) and/or 40 CFR Part 61, Subpart H, Section 61.96), prior approval from WDOH and/or EPA Region 10 is required. As an example, the following alternative method has been previously used for estimating potential emissions:
    - Multiply the annual possession quantity of each radionuclide by material-specific spill-release fractions rather than using the release fractions identified in WAC 246-247-030(21)(a) and 40 CFR Part 61, Appendix D.

Method 1 is authorized by 40 CFR Part 61, Subpart H, for calculating potential emissions. Historically, EPA Region 10 has also approved the use of alternative Methods 2 through 4 as well as the example provided in Method 5.

Alternative methods (i.e., Method 5) usually require a more extensive review and approval process. However, the use of previously approved methods should require a less extensive review and approval cycle compared with a method that uses a new technology or methodology.

2.1.1 Method 1: Annual Possession Quantity

Method 1 is prescribed in 40 CFR Part 61, Appendix D, and in WAC 246-247-030(21). The methods described by these regulations are substantially the same, with a few minor differences. The method in WAC 246-247-030(21)(a) is as follows:

- Multiply the annual possession quantity of each radionuclide by the release fraction for that radionuclide, depending on its physical state. Use the following release fractions:
  (i) 1 for gases;
  (ii) 10^{-3} for liquids or particulate solids; and
  (iii) 10^{-6} for solids.
- Determine the physical state for each radionuclide by considering its chemical form and the highest temperature to which it is subjected. Use a release fraction of 1.0 if the radionuclide is subjected to temperatures at or above its boiling point; use a release fraction of 10^{-3} (equivalent to 1.0 E-03) if the radionuclide is subjected to temperatures at or above its melting point but below its boiling point. If the chemical form is not known, use a release fraction of one for any radionuclide that is heated to 100°C or more, boils at a temperature of 100°C or less, or is intentionally dispersed into the environment.

Method 1 is typically used for PNNL radioactive air pollutants NOC applications. Other release fractions may be used only with WDOH approval as provided by Method 5. Methods 2 through 5 are described below in more detail.

2.1.2 Method 2: Back-Calculating Emissions and *In Situ* Measurements

WAC Chapter 246-247-030(21)(b) states that with approval, a back-calculation using measured emission rates and *in situ* measurements of the control-equipment efficiencies can be used to estimate potential emissions. Control-equipment efficiencies should be obtained using the methods prescribed by American Society of Mechanical Engineers (ASME) N509, *Testing of Nuclear Air Treatment Systems* (1999).[1]

Most of the Hanford emission-control equipment consists of high-efficiency particulate air (HEPA) filter systems. The *Handbook for Use with DOE-STD-1269-2022 "Air Cleaning Systems in DOE Nuclear Facilities*" (DOE-HDBK-1169-2022, Chg Notice 1; DOE 2023) provides a decontamination factor of 3,333 (rounded to 3,000) for a HEPA filter with a nominal stage efficiency of 99.97%. For series redundancy, an increased decontamination factor of $3{,}000^n$ for HEPA filter systems, in which "n" represents the number of HEPA filters in series, may be appropriate presuming the HEPA filters in series each have a minimum filtration efficiency of 99.97%. WDOH and EPA have allowed the use of a decontamination factor of $3{,}000^n$ for systems using "n" banks of HEPA filters in series. The potential emissions are then calculated by multiplying the actual annual emissions by the decontamination factor (i.e., $3{,}000^n$).

Method 2 can be extremely conservative for a contaminated system. When processing in a facility no longer occurs, the resuspension of contamination downstream of the HEPA filters can dominate the airborne releases from that facility. Multiplying those releases by $3{,}000^n$ can overestimate the potential emissions by an order of magnitude or more (Barnett and Davis 1996).

[1] The WAC still refers to ASME N509; however, it has been superseded by ASME N511 (2013). ASME N511 (2022) is the most current revision.

2.1.3 Method 3: Control Device and *In Situ* Measurements

WAC Chapter 246-247-030(21)(c) states that with approval, measurements of the quantities of radionuclides captured in the control device, coupled with *in situ* measurements of the control-equipment efficiencies, can be used to estimate potential emissions. Several variations of this method are available. Two variations are described in Sections 2.1.3.1 and 2.1.3.2.

2.1.3.1 Method 3.1: Control Device Inventory

Representative samples taken from the collection media in a control device are used to estimate the total radionuclide inventory within that control device. Isotopic analyses are performed on the samples. The total radionuclide inventory in the control device is estimated using the sample results, operating history of the device, and the appropriate radioactive-decay corrections. An annual release rate is calculated based on the total radionuclide inventory in the control device, its operating history, and its collection efficiency. The potential emissions, in the absence of the control device, are then calculated by dividing the annual release rate by the collection efficiency of the control device (Snyder and Barnett 2016).

2.1.3.2 Method 3.2: Control Device NDA

A nondestructive assay (NDA) measurement is used to determine the radionuclide inventory of a control device. The radionuclide inventory in a control device is derived using the NDA results, operating history for the device, and the appropriate radioactive-decay corrections. An annual release rate is calculated based on the radionuclide inventory of the control device, its operating history, and its collection efficiency. In the absence of the control device, potential emissions are then calculated by dividing the annual release rate by the collection efficiency of the control device.

The NDA dose assessment method most frequently used at the Hanford Site uses either a sodium-iodide or high-purity germanium gamma-ray detector to quantify the gamma-emitting radionuclides collected by the control device. An annual release rate is calculated for each gamma-emitting radionuclide. Annual release rates for non-gamma-emitting radionuclides are calculated using ratios obtained from actual radionuclide emissions measurements or inventory data (Barnett 1995).

2.1.4 Method 4: Measurement Upstream of Control Device

WAC Chapter 246-247-030(21)(d) states that with approval, effluent samples collected upstream from all control devices can be used to estimate potential emissions in the absence of the control devices.

Representative air samples are collected at a location upstream from all control devices. The samples are analyzed for expected radionuclides to determine their concentrations in the effluent stream. The potential emissions, in the absence of control devices, are then calculated by multiplying the radionuclide concentrations by the annual discharge volume.

2.1.5 Method 5: Alternative Methods

WAC Chapter 246-247-030(21)(a) states that with WDOH approval, other release fractions may be used to estimate potential unabated emissions. This would be similar to the example provided previously.

Other alternative methods need to be adequately documented and submitted to WDOH and/or EPA for approval. Additional time is required for the review and approval of alternative methods.

3.0 PNNL-Richland Campus PTE

3.1 Estimating Dose from Potential Emissions

Dose-per-unit-release factors are prepared to facilitate the estimation of the PTE total effective dose (TED) to the MPR from the PNNL-Richland campus. CAP88-PC or other approved software is required for this purpose by EPA regulations in 40 CFR Part 61, Subpart H, and by Washington State in WAC 246-247. The calculations for this document were performed using the CAP88-PC Version 4.1.1 software package (EPA 2020).

The CAP88-PC Version 4.1.1 software package incorporates a few significant changes over the previous version. Compared to CAP88-PC Version 4.0 (Rosnick 2014), Version 4.1.1 updates the dose/risk data from DCFPAK2.2 (Eckerman and Leggett 2008) to DCFPAK3.02 (Eckerman and Leggett 2013) as well as some user enhancements (EPA 2020). While not a substantial DCFPAK update, it does result in small, notable changes in results. DCFPAK3.02 also corrected an error in the module calculating remainder dose, corrects the nuclear data file, uses of the ICRP lung deposition values as a function of the activity median aerodynamic diameter (i.e., amad) to improve the agreement with ICRP Publication 72 values.[1] The DCFPAK update results in additional dose and risk coefficient data for 151 more isotopes included in the software. Updated inhalation coefficients for radionuclides with special chemical forms (e.g., iodine) were also included with the DCFPAK update.

Incorporating the DCFPAK3.02 dataset provides some updates to radionuclide physical data, dose factors (assumed dose integration period after intake of 50 yr for adults), risk factors (FGR 13 [Eckerman et al. 1999] with updated ICRP Publication 107 decay chains), and decay chain (ICRP Publication 107 [ICRP 2008]) information. DCFPAK3.02 implementation includes weight factors and committed equivalent dose coefficients for 25 organs, plus a "26th organ" that is the effective dose.

Table 3.1. List of Organ Doses Reported in CAP88-PC Version 4.1.1

Adrenals	Upper Large Intestine Wall	Red Bone Marrow	Heart Wall
Urinary Bladder Wall	Lower Large Intestine Wall	Skin	Uterus
Bone Surface	Kidneys	Spleen	Extra-thoracic Region
Brain	Liver	Testes	Lung[(a)]
Breasts	Muscle	Thymus	"Whole body Effective Dose" [(b)]
Stomach Wall	Ovaries	Thyroid	-
Small Intestine Wall	Pancreas	Gall Bladder Wall	-

(a) Lung model of ICRP Publication 66 (ICRP 1994)
(b) Quotes used because it aligns with the tissue dose notion but is the whole-body dose estimate.

[1] Information provided at: https://www.epa.gov/radiation/tools-calculating-radiation-dose-and-risk. Accessed August 8, 2025.

As indicated in the CAP88-PC User Guide, the food chain dose uses the methodology of Reg Guide 1.109 (NRC 1977). Environmental (plant and food chain) transport factors are those from the National Council on Radiation Protection and Measurements Report No. 123 (NCRP 1996).

Although there are many additional modeling details, a general explanation of what the unit dose factor represents is as follows. CAP88-PC Version 4.1.1 models a continuous annual 1 Ci release with a consecutive release assumed for the user-entered build-up period (100-yr used herein) minus one year. This effectively models buildup in the soil for routine facility operations and progeny in-growth, based on the 1 Ci emission each year (the stated annual emission rate). Then, on the final year of the build-up period another 1 Ci/yr emission is modeled and annual average air concentration is calculated based on the release.

- The result is based on one meteorological file for each year of modeled emissions.
- Any prior history of emissions that occurred at a facility is not included in the resulting dose, just the annual emission rate entered for the CAP88-PC case.

This report provides dose results for the parent plus decay chain members. The number of decay chain members included in the parent+D dose followed the guidance of DC_PAK3.02 (e.g., some additional chain member doses are or can be included in CAP88-PC output but the dose contribution of later chain members is insignificant compared to earlier chain member contributions). Parent+D dose-per-unit-release factor changes from the prior revision are summarized in Table 3.2. Table 3.2 does not include nuclides that are new to Revision 5 (i.e., nuclide was not included in Revision 4). These new nuclides in Revision 5 are indicated in Table 3.3.

Table 3.2. Parent-only Values Differences from Prior Report[(a)]

Parent-only Values Added	Parent-only Values Removed
Rb-86m	Pd-111
Au-195m	In-114m
Am-244m	Gd-150
-	U-235m
-	Bk-248m

(a) Prior report is Snyder and Barnett 2016

3.2 List of Approved Surrogate Radionuclides

Table 3.3 indicates the nuclides that are newly added as well as nuclides requiring surrogates. The nuclides requiring surrogate isotopes are not in the CAP88-PC Version 4.1.1 library. Surrogate radionuclides were selected to represent those isotopes when calculating the PTE dose. The regulatory authority (WAC 246-247-035) will approve surrogate radionuclides. WDOH 2025 indicates approval for surrogates new to this revision, and are applicable to operations at the Richland and Sequim campuses as well as PNNL facilities on the Hanford Site. The same nuclides that used surrogates in Snyder and Barnett 2016 still required surrogates in this revision.

Multiple methods were used to prepare the dose-per-unit-release factors for isotopes that were not in the CAP88-PC Version 4.1.1 library. The approaches used are listed in order of preference below and may be used in combination. The method adopted for an unavailable nuclide in the prior version of this

document was retained. Methods used to estimate dose for radionuclides not in the CAP88-PC Version 4.1.1 library include the following:

- A chemically and radiologically similar isotope (i.e., same or related element, similar half-life, similar radiological decay mode) that should be conservative for the missing isotope was identified. This includes consideration of Q values.
- Where the missing isotope had a metastable variant in the CAP88-PC Version 4.1 database, the related isotope from the library was used because the beginning and end states, and the total decay energy, are generally the same.
- External references support use of a specific surrogate in CAP88-PC (e.g., Harshman and Scofield 2023).
- For very short-lived isotopes (i.e., the half-life is less than about 2 hours) that have complex decay chains, the first longer-lived decay product was used as the surrogate. The dose-per-unit-release factor for the surrogate was then adjusted to account for the quantity of surrogate that would result from the decay of 1 Ci of the parent isotope.

An additional measure may be applied to the last bulleted item, above. To avoid the use of a grossly overestimated PTE dose factor, a surrogate nuclide adjustment factor can be applied based on half-lives and decay chain fractions. Values for short-lived isotopes are based on dose from the isotope first long-lived decay product, adjusted for quantity of the decay product that results from decay of the parent isotope. In mathematical terms, with half-lives indicated in the same time scale:

$$Ci_{surrogate} = Ci_{parent} * (\text{half-life}_{parent} / \text{half-life}_{surrogate})$$

Where other options did not apply or were not viable, conservative isotope values of Cs-137+D for beta/gamma emitters and Pu-239 for alpha emitters were used. For total natural uranium measurements (U-234, U-235, and U-238), apply the U-235 dose factor because it maximizes the PTE dose estimate result. However, also consider that natural uranium radioactivity is approximately 49.2% U-234, 2.2% U-235, and 48.6% U-238 (NRC 2023).

Dose factors presented in this report represent prospective estimates of potential radiation dose rates to the MPR following release of radioactive effluents to the ambient air from the PNNL-Richland campus. Assumptions and input for the CAP88-PC software calculations consisted of the MPR location relative to the facility, long-term meteorological data appropriate for the facility location, release-point characteristics, food-production options, the candidate list of radionuclides that could be emitted, and a release rate. Inputs to the code are summarized in Table 3.4.

Table 3.3. Newly Added Nuclides; Unavailable Nuclides and their Surrogates (DOE 2009, WDOH 2025); Radioiodine-specific Unavailable Chemical Forms

Radionuclides New to Revision 5[a]	Radionuclides Requiring Surrogates (Surrogate)	Iodines with No CAP88-PC Version 4.1.1 Vapor Form Available (Particulate forms used as Surrogates)
Na-24m	C-15 (use C-11)	I-122
Cl-38	NEW Na-24m (Na-24)	I-130m
Ni-66+D	NEW Ge-71m (Ge-71)	I-134m
Ge-71m	NEW Ge-73m (Ga-73)	-
Ge-73m	NEW Ge-77m+D (Ge-77+D)	-
Ge-77m+D	Kr-90+D (Kr-89+D[c])	-
Zr-98+D	NEW Zr-98+D (Nb-98m+D)	-
Zr-99+D	NEW Zr-99+D (Nb-99+D)	-
Zr-100+D	NEW Zr-100 (Cd-119)	-
Nb-97m	NEW Nb-97m (Nb-97 *2)	-
Nb-98+D	NEW Nb-98 (Nb-98m)	-
Nb-103+D	NEW Nb-100 (Cd-119)	-
Nb-100+D	NEW Nb-101+D (Mo-101+D)	-
Nb-101+D	NEW Nb-103 (Ru-103+D)	-
Mo-103+D	NEW Mo-103 (Ru-103)	-
Mo-104+D	NEW Mo-104+D (Tc-104+D)	-
Mo-105+D	NEW Mo-105+D (Tc-105+D)	-
Tc-103+D	NEW Tc-103+D (Ru-103+D)	-
Tc-106+D	NEW Tc-106+D (Ru-106+D)	-
Ag-105	Rh-105m (use Rh-105)	-
Ag-106m	NEW In-116 (In-116m)	-
In-116	NEW Zr-100 (Cd-119)	-
Xe-139+D	NEW Xe-139+D (Cs-139+D)	-
Cs-141+D	NEW Cs-141+D (Ba-141+D)	-
Ba-143+D	NEW Ba-143+D (La-143+D)	-
La-144+D	NEW La-144+D (Ce-144+D)	-
Eu-146+D	Ce-142 (Ce-144+D)	-
Eu-149	I-133m+D (I-133+D)	-
Dy-169+D	NEW Dy-169 (Er-169)	-
Lu-172	Hf-178 (Hf-178m)	-
Lu-172m	NEW Pt-199m+D (Pt-199+D)	-
Lu-173	NEW Po-208 (Po-210*2)	-
Hf-172+D	NEW Po-209 (Po-210*2)	-
Re-183	Rn-224+D (Fr-224+D)[b]	-
Pt-199m+D	-	-
At-211+D	-	-
Fr-224+D[b]	-	-
Pu-246+D	-	-
Es-253+D	-	-

(a) Most nuclides were added because they are new to PNNL's WDOH list of potential releases from site operations. The following nuclides were added because they were required as surrogates for some of these new nuclides: Fr-224, Ge-73, Tc-105, Mo-101, La-143, Nb-98m, and Tc-104.

(b) Fr-224+D was added as a new surrogate for Rn-224, which previously had used Ra-224 (adjusted) as a surrogate because it was its first long-lived progeny (see Table 3.4 of Snyder and Barnett 2016). The Rn-224 progeny are first Fr-224 then Ra-224.

(c) Kr-89+D is a new surrogate radionuclide for Kr-90+D. Snyder and Barnett 2016 surrogate was Sr-90+D with an adjustment for parent and surrogate half-life, but the Kr-89 surrogate improves the dosimetric estimate (Harshman and Scofield 2023).

3.3 Parameters and Data Used to Demonstrate Compliance with Air Pathway Radiation Dose Standards at the PNNL-Richland Campus

A number of parameters are input by the user to determine the unit dose factors for the MPR and MA of the PNNL-Richland campus. Some specific parameters are indicated in Table 3.4, along with the basis for each assumption as applicable. CAP88-PC Version 4.1.1 default values were used for many inputs. The history of the data and parameters that have been applied in the PNNL-Richland campus calculations is described in PNNL-17847, Revision 4.

Historical information going back to the early 1970s that describes environmental dose evaluations can be found in Snyder and Barnett 2016. The current environmental dose evaluation information for annual human and biota dose assessments can be found in Snyder and Cooley 2024.

PNNL-Richland campus-specific data used with CAP88-PC Version 4.1.1 to calculate dose-per-unit-release factors include the meteorological data appropriate to the source location and type of evaluation. For the PNNL-Richland campus, long-term data collected at the 300 Area meteorology station, 10-m instrumentation height, were used. Data collection methods as well as annual historical summaries may be found in Hoitink et al. (2005) and Duncan (2007). Data were formatted as required for use with CAP88-PC.

PNNL-Richland campus-specific parameters used to calculate the dose-per-unit-release factors are listed in Table 3.4. Values presented are used to calculate doses for a hypothetical offsite member of the public who receives the highest exposure to airborne emissions. The offsite MPR has historically been assumed to be an ever-present, self-sufficient farmer located near the site boundary. In this case, the offsite MPR is located at an office building adjacent to the PNNL-Richland campus boundary. However, the assumptions used for the dose calculations conservatively treat this individual as a 24/7 resident who produced all their food at that location. The same approach was applied to the hypothetical receptor at the MA location.

Table 3.4. Inputs and Assumptions of PNNL-Richland Campus MPR and MA Dose-per-Unit-Release Factor Calculations

Parameter	Units	Assumption or Value Used	Basis for Assumptions or Values
Facility location	-	Richland, WA	Used to determine food production rates—from CAP88-PC database.
MPR location	-	640 m SSE (PNNL-Richland campus Boundary at 3179 George Washington Way, Richland, WA)	Distance and direction from the PNNL-Richland campus PSF emission unit to nearest residence, school, or business where a member of the public could be located (see Figure 1.1, white star).
MA location	-	580 m NW (of 3430 Building) (scrubland, about 580 m [1900 ft] north of the intersection of Stevens Drive and Horn Rapids Rd, Richland, WA)	Distance and direction from the PNNL-Richland campus PSF emission unit to the location of the offsite maximum modeled air concentration (see Figure 1.1, white circle).
Build-up time	yr	100	A 100-year assumption is the current CAP88-PC default and is an overestimating assumption for facility operations and unchanging MEI residency.
Wind data[(a)]	m/sec (Fraction of time)	Hanford Site 300 Area Meteorology Station (Station 11) – 10 m height 2014–2023 long-term avg: wind speed, direction, atmospheric stability	Nearest wind tower to PNNL-Richland campus – release location. Long-term data used for prospective assessments, most recent 10 years available were used.
Annual precipitation[(a)]	cm/yr	17.2	Average Hanford Meteorological Station precipitation rate (2014−2023).
Average temperature[(a)]	Celsius	12.9	Average Hanford Meteorological Station temperature (2014−2023).
Absolute humidity	g/m^3	8.00	CAP88-PC default assumed. Likely in 6 g/m^3 range, but higher value is conservative (over-estimating).
Source type	-	Stack	Emissions generally originate from a stack or vent. Sometimes a source is characterized as a fugitive emission (i.e., not from a stack or vent).
Stack dimensions	m	Height = 10.0 Diameter = 1.0	Default effective stack height used for short stacks consistent with the physical height and diameter of PNNL-Richland campus emission units.
Plume rise model	-	None	No additional plume rise assumption applied to stack height.
Food source scenario	-	Local (all food produced at receptor location)	Conservative assumption.
Beef cattle density	$\#/km^2$	0.0562 per ha	CAP88-PC, Washington, default assumed.
Milk cattle density	$\#/km^2$	0.015 per ha	CAP88-PC, Washington, default assumed.
Land fraction cultivated for vegetables	-	0.052	CAP88-PC, Washington, default assumed.
Nuclide release rate	Ci/yr	1.0	Default basis to make determination of dose-per-unit-release factor.
Nuclide chemical form, type, size	-	Isotope specific	CAP88-PC defaults used, except when variable chemical forms or types are specifically indicated in dose factor table.

(a) Meteorological data acquired from the Hanford Site Meteorological/Climatological Services managed by Hanford Mission Integration Solutions.

Table 3.5 indicates the distances to potential MPRs and PNNL-Richland campus boundary (potential MA receptor) locations in each of the 16 directions evaluated by CAP88-PC. These locations were reviewed to determine the highest air concentrations (i.e., least dispersion of annual emission as indicated by Chi/Q values) in each direction, in order to determine the MPR and MA locations appropriate for PTE dose factor determination. While the smallest distances are listed, the assessor would also evaluate farther offsite distances in each direction to make certain higher air concentrations are not found downwind of the smallest distance.

Table 3.5. PNNL-Richland Campus Potential Receptor Locations and Distances to Boundary

Direction from PSF Building (10m stack assumption)	Smallest Distance (m) to the Potential MPR Location (m relative to indicated Building)			Smallest Distance (m) to the Campus Boundary Potential MA Location (m relative to indicated Building)		
	3410	**3420**	**3430**	**3410**	**3420**	**3430**
N	1185	1125 Hanford Site	1185	-	1125 Hanford Site	-
NNE	1270	1210 Hanford Site	1285	-	1210 Hanford Site	-
NE	1490 res, far river	995	1135	905 near river	-	-
ENE	1460 res far river	820	935	735 near river	-	-
E	1440 res far river	780	890	715 near river	-	-
ESE	425 busi	505	665	425 far side LSB	-	-
SE[(a)]	**630 busi**	**710 busi**	**610 busi**	-	-	610 busi
SSE[(a)]	**640 busi**	**850 busi**	1125 busi	640 GWWay	-	-
S	1825	1670	1605 n/a road & scrub	-	-	1605 4th St
SSW	1030	1090	990 busi	-	-	990 Stevens, just N of Battelle Blvd
SW	750	730	(590) n/a road & scrub	-	-	590 Stevens
WSW	655	560	(430) n/a road & scrub	-	-	430 Stevens
W	600	520	(415) n/a road & scrub	-	-	415 Stevens
WNW	650	560	(450) n/a road & scrub	-	-	450 Stevens
NW	760	620	(580) n/a road & scrub	-	-	**580 PNL-1**
NNW	1285	1215	(1035) n/a road & scrub	-	-	1035 Stevens

PSF buildings with major emissions units include 3410, 3420, and 3430.
Bold values indicate likely critical receptor locations for site meteorology.
res = residential structure.
busi = business (Hanford Site, offices, or restaurant).
"-" = The MA distance is greater than the indicated MA location for this facility and direction.
(a) Dispersion values are typically highest in SE and SSE directions, so all PSF distances indicated as potential MPR locations. Review is necessary to determine current occupants (PNNL or other business) in the office location.

3.4 Richland Campus MPR and MA Location Dose Factors

The MPR and MA locations' dose-per-unit-release factors in Table 3.6 are used to estimate potential radiological dose from the PNNL-Richland campus PSF emission units for purposes of permitting. The doses are estimated using PTE release rates (Ci/yr) for dispersible radionuclides expected to be present in the facility, multiplied by corresponding values in Table 3.6 for a 1-Ci/yr release of each radionuclide. Doses for all radionuclides potentially released from the emission unit are combined to estimate the total annual MPR and/or MA PTE dose. See Section 3.5 for guidance in estimating dose from a radiological facility located in a different region of the PNNL-Richland campus (i.e., other than PSF) for purposes of permitting.

Many radionuclides decay into other radionuclides, creating a radioactive-decay chain consisting of a parent nuclide and its radioactive progeny (decay products, daughters). CAP88-PC output includes both the parent and radioactive progeny doses, separately. As appropriate and required, contributions to the dose from ingrowth of decay products are included in Table 3.6 for each radionuclide. Doses listed as "+D" for the parent radionuclide of each decay chain include the contribution from other radionuclides produced by decay of the parent radionuclide following release from the emission unit to the environment. The "+D" values assume release of 1 Ci/yr of the parent isotope with no other decay-chain members present initially. In cases where the radioactive progeny contribute substantially (specifically, greater than 10%) to the dose following release of the parent isotope, the dose contribution from the parent isotope alone is listed separately in the table. This can provide useful detail when reviewing emission-specific dose contributions.

If members of a decay chain are included in the estimated emissions, the dose for each decay-product radionuclide is calculated separately in the same manner used for the parent isotope. The doses from each member of the chain and its decay products are then combined with doses from all other radionuclides included in the potential emissions to estimate the total PTE dose.

Table 3.6 (radionuclides) lists PNNL-Richland campus dose-per-unit-release factors for the PNNL-Richland campus MPR and MA locations (refer to Table 3.4), by radionuclide. The calculations were performed for a 1 curie per year (Ci/yr) release rate for each radionuclide. Values in the tables are calculated to be conservative estimates for all emission unit locations on the PNNL-Richland campus and may be used for prospective estimates of radiation dose.

As indicated in Section 3.1, where other options did not apply or were not viable, conservative isotope values of Cs-137+D for beta/gamma emitters and Pu-239 for alpha emitters were used. For total natural uranium measurements (U-234, U-235, and U-238), apply the U-235 dose factor because it maximizes the PTE dose estimate result. However, also consider that natural uranium radioactivity is approximately 49.2% U-234, 2.2% U-235, and 48.6% U-238 (NRC 2023).

Table 3.6. Maximum Public Receptor and Maximum Air Location Dose-per-Unit-Release Factors for the PNNL-Richland Campus (PSF Emission Location)

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
H-3 (V)	6.36E-04	8.50E-04
H-3 (E)	5.68E-04	7.59E-04
H-3 (O)	1.40E-03	1.87E-03
H-3 (F)	5.79E-04	7.75E-04
H-3 (M)	7.23E-04	9.68E-04
H-3 (S)	1.53E-03	2.05E-03
Be-7	7.06E-03	9.46E-03
Be-10	1.77E-01	2.37E-01
C-11	9.13E-04	1.23E-03
C-11 (CO)	8.87E-04	1.20E-03
C-11 (CO2)	8.87E-04	1.20E-03
C-14	7.40E-02	9.90E-02
C-14 (CO)	6.89E-02	9.21E-02
C-14 (CO2)	6.89E-02	9.21E-02
C-15	C-11	C-11
N-13	7.18E-04	9.75E-04
O-15	1.94E-04	2.76E-04
O-19	6.54E-07	9.87E-07
F-18	1.26E-03	1.68E-03
Na-22	5.86E+00	7.85E+00
Na-24	1.16E-02	1.55E-02
Na-24m	Na-24	Na-24
Mg-27	6.43E-04	8.74E-04
Mg-28+D	1.31E-02	1.76E-02
Mg-28	7.89E-03	1.06E-02
Al-26	6.80E+01	9.11E+01
Al-28	4.30E-04	6.10E-04
Si-31	2.38E-04	3.19E-04
Si-32+D	2.05E+00	2.74E+00
Si-32	7.66E-02	1.03E-01
P-32	6.10E-02	8.17E-02
P-33	1.38E-02	1.84E-02
S-35	5.63E-02	7.54E-02
Cl-36	6.51E+01	8.72E+01
Cl-38	1.67E-03	2.25E-03
Ar-37	0.00E+00	0.00E+00
Ar-39	2.54E-06	3.40E-06
Ar-41	1.32E-03	1.77E-03
Ar-42+D	1.16E-05	1.49E-05
Ar-42	2.79E-06	3.73E-06
K-40	1.24E+01	1.66E+01
K-42	1.89E-03	2.54E-03
Ca-41	1.32E-01	1.77E-01
Ca-45	3.11E-02	4.16E-02
Ca-47+D	2.07E-02	2.77E-02
Sc-44	3.49E-03	4.67E-03
Sc-44m+D	1.85E-02	2.49E-02
Sc-44m	5.93E-03	7.95E-03
Sc-46	4.41E-01	5.90E-01
Sc-47	2.91E-03	3.90E-03
Sc-48	2.08E-02	2.78E-02
Ti-44+D	4.34E+01	5.81E+01
Ti-44	3.31E+00	4.43E+00
Ti-45	1.36E-03	1.82E-03
Ti-51	2.09E-04	2.87E-04
V-48	1.36E-01	1.82E-01
V-49	1.01E-03	1.35E-03
Cr-49+D	1.10E-03	1.48E-03
Cr-51	3.16E-03	4.23E-03
Cr-55	8.56E-06	1.19E-05
Mn-52	5.51E-02	7.38E-02
Mn-52m+D	2.24E-03	3.02E-03
Mn-53	1.08E-02	1.44E-02
Mn-54	6.31E-01	8.45E-01
Mn-56	2.52E-03	3.38E-03
Fe-55	4.27E-02	5.72E-02
Fe-59	2.04E-01	2.74E-01
Co-56	8.16E-01	1.09E+00
Co-57	1.00E-01	1.34E-01
Co-58	2.15E-01	2.88E-01
Co-58m+D	9.11E-04	1.22E-03
Co-58m	4.19E-05	5.60E-05
Co-60	1.05E+01	1.41E+01
Co-60m+D	4.25E-05	5.70E-05
Co-60m	5.33E-06	7.24E-06
Ni-56+D	8.26E-02	1.11E-01
Ni-56	3.30E-02	4.41E-02
Ni-57+D	1.10E-02	1.47E-02
Ni-59	1.99E-02	2.66E-02
Ni-63	4.19E-02	5.61E-02
Ni-65	9.70E-04	1.30E-03
Ni-66+D	9.26E-03	1.24E-02
Ni-66	7.97E-03	1.07E-02
Cu-64	7.27E-04	9.74E-04
Cu-66	6.27E-05	8.63E-05
Cu-67	2.33E-03	3.11E-03
Zn-65	1.65E+00	2.21E+00
Zn-69	7.45E-05	1.00E-04
Zn-69m+D	1.78E-03	2.40E-03
Ga-67	2.03E-03	2.71E-03
Ga-68	1.14E-03	1.53E-03
Ga-70	5.65E-05	7.63E-05
Ga-72	8.06E-03	1.08E-02
Ga-73	9.30E-04	1.25E-03
Ge-68+D	1.71E+00	2.30E+00
Ge-68	1.05E+00	1.41E+00
Ge-69	5.41E-03	7.25E-03
Ge-71	3.94E-04	5.27E-04
Ge-71m	Ge-71	Ge-71
Ge-73m	Ga-73	Ga-73
Ge-75	1.47E-04	1.97E-04
Ge-77+D	3.46E-03	4.62E-03
Ge-77m	Ge-77+D	Ge-77+D
As-73	1.61E-02	2.15E-02
As-74	5.56E-02	7.44E-02
As-76	4.07E-03	5.45E-03
As-77	1.17E-03	1.56E-03
Se-75	7.34E-01	9.83E-01
Se-77m	1.36E-09	2.31E-09
Se-79	2.87E+00	3.85E+00

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
Se-79m+D	3.32E-06	4.61E-06
Br-82	1.39E-02	1.87E-02
Br-82m+D	3.36E-05	4.49E-05
Br-82m	2.03E-06	2.78E-06
Br-83+D	1.52E-04	2.03E-04
Br-84	1.92E-03	2.58E-03
Br-84m	1.63E-03	2.24E-03
Br-85+D	2.86E-05	4.00E-05
Kr-81	8.45E-07	1.13E-06
Kr-81m+D	7.42E-11	1.65E-10
Kr-83m	2.36E-08	3.16E-08
Kr-85	5.33E-06	7.13E-06
Kr-85m+D	1.50E-04	2.00E-04
Kr-87+D	8.40E-04	1.13E-03
Kr-88+D	2.26E-03	3.01E-03
Kr-89+D	1.02E-03	1.41E-03
Kr-89	7.21E-04	1.01E-03
Kr-90	Kr-89+D	Kr-89+D
Rb-81+D	1.08E-03	1.45E-03
Rb-81	9.09E-04	1.22E-03
Rb-81m+D	1.01E-04	1.35E-04
Rb-81m	6.07E-05	8.17E-05
Rb-82	8.01E-05	1.17E-04
Rb-82m	5.17E-03	6.92E-03
Rb-83+D	2.48E-01	3.32E-01
Rb-84	1.77E-01	2.37E-01
Rb-84m+D	3.78E-04	5.08E-04
Rb-84m	3.40E-04	4.58E-04
Rb-86	7.22E-02	9.67E-02
Rb-86m+D	2.27E-05	3.31E-05
Rb-86m	2.01E-05	2.96E-05
Rb-87	1.64E+00	2.19E+00
Rb-88	6.91E-04	9.34E-04
Rb-89+D	2.00E-03	2.70E-03
Rb-90+D	6.55E-04	9.21E-04
Rb-90m+D	1.65E-03	2.28E-03
Sr-82+D	1.98E-01	2.65E-01
Sr-82	1.20E-01	1.61E-01
Sr-83+D	6.02E-03	8.06E-03
Sr-83	4.45E-03	5.96E-03
Sr-85	9.63E-02	1.29E-01
Sr-85m+D	2.78E-04	3.73E-04
Sr-85m	2.29E-04	3.08E-04
Sr-87m+D	4.46E-04	5.97E-04
Sr-89	9.58E-02	1.28E-01
Sr-90+D	1.31E+01	1.75E+01
Sr-90	1.15E+01	1.54E+01
Sr-91+D	2.96E-03	3.97E-03
Sr-91	2.57E-03	3.44E-03
Sr-92+D	2.42E-03	3.25E-03
Y-88	6.83E-01	9.15E-01
Y-89m	4.97E-09	9.07E-09
Y-90	5.36E-03	7.17E-03
Y-90m+D	1.12E-03	1.50E-03
Y-91	7.19E-02	9.63E-02
Y-91m+D	5.60E-04	7.52E-04
Y-92	9.23E-04	1.24E-03
Y-93+D	1.56E-03	2.09E-03

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
Zr-88+D	5.90E-01	7.90E-01
Zr-88	9.25E-02	1.24E-01
Zr-89	1.19E-02	1.60E-02
Zr-89m+D	2.88E-04	3.99E-04
Zr-93+D	6.69E-02	8.96E-02
Zr-93	5.53E-02	7.41E-02
Zr-95+D	2.56E-01	3.43E-01
Zr-95	1.40E-01	1.88E-01
Zr-97+D	6.45E-03	8.63E-03
Zr-97	5.22E-03	6.98E-03
Zr-98+D	Nb-98m+D	Nb-98m+D
Zr-99+D	Nb-99+D	Nb-99+D
Zr-100	Cd-119	Cd-119
Nb-91	1.28E-01	1.71E-01
Nb-91m+D	1.88E-02	2.52E-02
Nb-92	3.91E+01	5.23E+01
Nb-92m	2.72E-02	3.64E-02
Nb-93m	1.13E-02	1.51E-02
Nb-94	4.07E+01	5.45E+01
Nb-94m+D	2.78E-06	3.82E-06
Nb-95	7.52E-02	1.01E-01
Nb-95m+D	9.30E-03	1.25E-02
Nb-95m	3.11E-03	4.16E-03
Nb-96	9.98E-03	1.34E-02
Nb-97	8.31E-04	1.11E-03
Nb-97m	2 * Nb-97	2 * Nb-97
Nb-98+D	Nb-98m	Nb-98m
Nb-98m	3.07E-03	4.13E-03
Nb-99+D	3.05E-07	4.10E-07
Nb-99	6.02E-10	1.14E-09
Nb-100+D	Cd-119	Cd-119
Nb-101+D	Mo-101+D	Mo-101+D
Nb-103+D	Ru-103+D	Ru-103+D
Mo-93+D	4.17E-01	5.60E-01
Mo-93m+D	4.37E-03	5.85E-03
Mo-99+D	4.82E-03	6.46E-03
Mo-99	4.13E-03	5.53E-03
Mo-101+D	1.37E-03	1.84E-03
Mo-103+D	Ru-103+D	Ru-103+D
Mo-104+D	Tc-104+D	Tc-104+D
Mo-105+D	Tc-105+D	Tc-105+D
Tc-95	2.67E-03	3.57E-03
Tc-95m+D	1.24E-01	1.66E-01
Tc-96	3.10E-02	4.15E-02
Tc-96m+D	2.76E-04	3.69E-04
Tc-96m	6.45E-05	8.66E-05
Tc-97	3.81E-01	5.10E-01
Tc-97m+D	3.35E-02	4.48E-02
Tc-98	4.38E+01	5.86E+01
Tc-99	2.41E+00	3.23E+00
Tc-99m+D	2.38E-04	3.19E-04
Tc-101	2.94E-04	3.98E-04
Tc-103+D	Ru-103+D	Ru-103+D
Tc-104	2.12E-03	2.86E-03
Tc-105+D	5.56E-04	7.57E-04
Tc-106+D	Ru-106+D	Ru-106+D
Ru-97+D	2.13E-03	2.86E-03
Ru-103+D	6.33E-02	8.47E-02

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
Ru-105+D	1.63E-03	2.19E-03
Ru-106+D	5.87E-01	7.86E-01
Ru-106	2.71E-01	3.63E-01
Rh-101	7.33E-01	9.82E-01
Rh-101m+D	4.02E-03	5.39E-03
Rh-102	2.95E-01	3.95E-01
Rh-102m+D	6.40E+00	8.57E+00
Rh-103m	6.25E-06	8.40E-06
Rh-104	2.85E-07	4.24E-07
Rh-104m+D	2.60E-05	3.60E-05
Rh-104m	9.22E-06	1.28E-05
Rh-105	1.24E-03	1.66E-03
Rh-105m	Rh-105	Rh-105
Rh-106	3.31E-07	4.98E-07
Pd-103+D	2.71E-03	3.62E-03
Pd-107	3.72E-03	4.99E-03
Pd-109	1.03E-03	1.38E-03
Pd-109m+D	5.20E-05	7.16E-05
Pd-111+D	1.30E-04	1.75E-04
Pd-112+D	4.82E-03	6.45E-03
Pd-112	3.10E-03	4.15E-03
Ag-105	6.08E-02	8.14E-02
Ag-106m	6.67E-02	8.93E-02
Ag-108	6.74E-06	9.53E-06
Ag-108m+D	4.04E+01	5.41E+01
Ag-109m	2.36E-08	3.52E-08
Ag-110	2.03E-08	3.09E-08
Ag-110m+D	1.73E+00	2.31E+00
Ag-111	9.72E-03	1.30E-02
Ag-111m+D	1.10E-06	1.49E-06
Ag-111m	1.67E-07	2.45E-07
Ag-112	1.46E-03	1.95E-03
Cd-107	2.49E-04	3.33E-04
Cd-109	1.18E-01	1.58E-01
Cd-111m	3.20E-04	4.30E-04
Cd-113	9.78E+00	1.31E+01
Cd-113m	3.66E+00	4.91E+00
Cd-115+D	5.26E-03	7.04E-03
Cd-115	4.41E-03	5.90E-03
Cd-115m+D	8.32E-02	1.11E-01
Cd-117+D	1.93E-03	2.60E-03
Cd-117m+D	3.59E-03	4.81E-03
Cd-119+D	5.38E-04	7.54E-04
In-106	2.07E-03	2.84E-03
In-111	3.69E-03	4.95E-03
In-111m+D	3.04E-04	4.15E-04
In-112	2.29E-04	3.10E-04
In-112m+D	1.31E-04	1.74E-04
In-112m	6.90E-05	9.31E-05
In-113m	3.35E-04	4.49E-04
In-114	9.85E-07	1.44E-06
In-114m+D	1.29E-01	1.72E-01
In-115	1.90E+00	2.54E+00
In-115m+D	3.85E-04	5.16E-04
In-116	In-116m	In-116m
In-116m	2.74E-03	3.68E-03
In-117+D	7.41E-04	9.95E-04
In-117m+D	3.99E-04	5.34E-04
In-117m	3.09E-04	4.15E-04
Sn-113+D	1.14E-01	1.53E-01
Sn-113	4.36E-02	5.84E-02
Sn-113m+D	2.13E-05	2.86E-05
Sn-113m	1.18E-05	1.59E-05
Sn-117m	1.69E-02	2.27E-02
Sn-119m	3.31E-02	4.43E-02
Sn-121	6.23E-04	8.34E-04
Sn-121m+D	1.77E-01	2.37E-01
Sn-123	1.37E-01	1.84E-01
Sn-123m	2.05E-04	2.76E-04
Sn-125+D	4.29E-02	5.75E-02
Sn-125	3.35E-02	4.49E-02
Sn-125m+D	2.56E-04	3.47E-04
Sn-126+D	5.60E+01	7.49E+01
Sn-126	3.23E+00	4.32E+00
Sb-122	7.13E-03	9.55E-03
Sb-122m+D	2.31E-05	3.17E-05
Sb-122m	1.73E-05	2.40E-05
Sb-124	3.21E-01	4.30E-01
Sb-124m+D	5.37E-05	7.70E-05
Sb-124n+D	4.17E-04	5.58E-04
Sb-124n	1.59E-05	2.14E-05
Sb-125+D	1.02E+00	1.37E+00
Sb-126	1.07E-01	1.44E-01
Sb-126m+D	1.38E-03	1.87E-03
Sb-127+D	1.30E-02	1.74E-02
Sb-128	7.08E-03	9.48E-03
Sb-128m+D	1.43E-03	1.94E-03
Sb-129+D	2.84E-03	3.81E-03
Te-121	3.25E-02	4.35E-02
Te-121m+D	3.57E-01	4.79E-01
Te-121m	1.72E-01	2.31E-01
Te-123	2.96E-01	3.96E-01
Te-123m+D	9.48E-02	1.27E-01
Te-125m	3.28E-02	4.39E-02
Te-127	3.65E-04	4.89E-04
Te-127m+D	1.00E-01	1.34E-01
Te-129+D	1.76E-04	2.36E-04
Te-129m+D	7.74E-02	1.04E-01
Te-129m	7.12E-02	9.54E-02
Te-131+D	1.07E-03	1.41E-03
Te-131	4.55E-04	6.13E-04
Te-131m+D	1.08E-02	1.44E-02
Te-131m	8.82E-03	1.18E-02
Te-132+D	2.69E-02	3.60E-02
Te-132	9.08E-03	1.22E-02
Te-133+D	1.08E-03	1.47E-03
Te-133	1.00E-03	1.36E-03
Te-133m+D	2.34E-03	3.14E-03
Te-134+D	1.49E-03	2.00E-03
Te-134	1.00E-03	1.35E-03
I-122	3.21E-04	4.62E-04
	Chemical form	Chemical
I-122(V)	n/a	form n/a
I-123+D	3.41E-03	4.70E-03
I-123(V)+D	9.43E-04	1.26E-03
I-124	5.13E-01	7.05E-01

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
I-124(V)	4.51E-02	6.03E-02
I-125	1.60E+01	2.20E+01
I-125(V)	5.19E-02	6.94E-02
I-126	5.72E+00	7.87E+00
I-126(V)	9.89E-02	1.32E-01
I-128	1.61E-04	2.23E-04
I-128(V)	2.75E-04	3.70E-04
I-129	4.02E+02	5.53E+02
I-129(V)	3.63E-01	4.85E-01
I-130	4.15E-02	5.71E-02
I-130(V)	8.68E-03	1.16E-02
I-130m+D	4.66E-04	6.42E-04
I-130m	7.29E-05	1.02E-04
I-130m(V)	Chemical form n/a	Chemical form n/a
I-131+D	2.15E+00	2.96E+00
I-131(V)+D	7.35E-02	9.83E-02
I-132	9.24E-03	1.27E-02
I-132(V)	3.35E-03	4.48E-03
I-132m+D	4.99E-03	6.88E-03
I-132m	1.04E-03	1.44E-03
I-132m(V)+D	9.89E-04	1.32E-03
I-132m(V)	7.93E-04	1.06E-03
I-133+D	2.93E-02	4.03E-02
I-133(V)+D	1.54E-02	2.06E-02
I-133m	I-133+D	I-133+D
I-134	5.04E-03	6.96E-03
I-134(V)	3.01E-03	4.03E-03
I-134m+D	3.84E-04	5.30E-04
I-134m	8.58E-05	1.23E-04
I-134m(V)	Chemical form n/a	Chemical form n/a
I-135+D	1.95E-02	2.68E-02
I-135	1.64E-02	2.25E-02
I-135(V)+D	4.88E-03	6.53E-03
Xe-122+D	5.47E-04	7.31E-04
Xe-122	4.83E-05	6.46E-05
Xe-123+D	6.29E-04	8.40E-04
Xe-123	6.14E-04	8.21E-04
Xe-125+D	8.78E-04	1.15E-03
Xe-125	2.38E-04	3.18E-04
Xe-127	2.50E-04	3.34E-04
Xe-127m+D	8.04E-06	1.17E-05
Xe-129m	2.03E-05	2.71E-05
Xe-131m	7.90E-06	1.06E-05
Xe-133	3.03E-05	4.05E-05
Xe-133m+D	2.85E-05	3.81E-05
Xe-135+D	2.42E-04	3.23E-04
Xe-135m+D	3.36E-04	4.54E-04
Xe-137+D	9.69E-05	1.34E-04
Xe-138+D	1.18E-03	1.58E-03
Xe-138	9.50E-04	1.28E-03
Xe-139+D	Cs-139+D	Cs-139+D
Cs-131	1.09E-03	1.46E-03
Cs-132	1.49E-02	2.00E-02
Cs-134	7.53E+00	1.01E+01
Cs-134m+D	5.04E-04	6.75E-04
Cs-134m	6.47E-05	8.67E-05
Cs-135	2.56E+00	3.43E+00
Cs-135m+D	1.66E-03	2.23E-03
Cs-136	1.17E-01	1.57E-01
Cs-137+D	1.64E+01	2.19E+01
Cs-137	8.41E+00	1.13E+01
Cs-138	2.45E-03	3.29E-03
Cs-138m+D	2.58E-04	3.51E-04
Cs-138m	1.31E-04	1.84E-04
Cs-139+D	2.65E-04	3.60E-04
Cs-140+D	8.99E-05	1.31E-04
Cs-141+D	Ba-141+D	Ba-141+D
Ba-131+D	1.80E-02	2.42E-02
Ba-131m+D	7.56E-05	1.02E-04
Ba-131m	6.29E-05	8.51E-05
Ba-133	2.80E+00	3.76E+00
Ba-133m+D	2.69E-03	3.61E-03
Ba-133m	1.53E-03	2.05E-03
Ba-135m	1.14E-03	1.53E-03
Ba-137m	1.56E-04	2.20E-04
Ba-139	2.36E-04	3.17E-04
Ba-140+D	1.04E-01	1.39E-01
Ba-140	3.53E-02	4.73E-02
Ba-141+D	9.01E-04	1.22E-03
Ba-142+D	9.50E-04	1.29E-03
Ba-142	8.21E-04	1.12E-03
Ba-143+D	La-143+D	La-143+D
La-137	5.68E-01	7.60E-01
La-138	3.10E+01	4.16E+01
La-140	1.47E-02	1.97E-02
La-141+D	5.71E-04	7.65E-04
La-142	3.07E-03	4.12E-03
La-143+D	3.08E-04	4.16E-04
La-144+D	Ce-144+D	Ce-144+D
Ce-139	5.86E-02	7.85E-02
Ce-141	2.25E-02	3.01E-02
Ce-142	Ce-144+D	Ce-144+D
Ce-143+D	3.59E-03	4.82E-03
Ce-144+D	3.41E-01	4.57E-01
Ce-144	2.28E-01	3.06E-01
Pr-142	1.92E-03	2.57E-03
Pr-142m+D	2.38E-05	3.18E-05
Pr-142m	1.57E-05	2.12E-05
Pr-143	1.36E-02	1.83E-02
Pr-144	9.15E-05	1.24E-04
Pr-144m+D	2.05E-05	2.70E-05
Pr-144m	3.51E-06	4.79E-06
Nd-144	2.91E+01	3.89E+01
Nd-147+D	1.47E-02	1.97E-02
Pm-143	2.05E-01	2.74E-01
Pm-144+D	1.37E+00	1.84E+00
Pm-145	2.98E-01	4.00E-01
Pm-146+D	3.23E+00	4.33E+00
Pm-147+D	2.26E-02	3.02E-02
Pm-148	1.81E-02	2.42E-02
Pm-148m+D	2.41E-01	3.23E-01
Pm-149	2.23E-03	2.98E-03
Pm-150	2.24E-03	3.00E-03
Pm-151+D	2.52E-03	3.37E-03

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
Sm-145+D	7.05E-02	9.44E-02
Sm-145	5.60E-02	7.50E-02
Sm-146	3.92E+01	5.24E+01
Sm-147	3.56E+01	4.76E+01
Sm-148+D	3.04E+01	4.07E+01
Sm-151	1.70E-02	2.28E-02
Sm-153	2.13E-03	2.85E-03
Sm-155+D	1.32E-04	1.78E-04
Sm-156+D	1.98E-03	2.66E-03
Sm-156	8.42E-04	1.13E-03
Sm-157+D	2.85E-04	3.87E-04
Eu-146+D	3.17E-02	4.24E-02
Eu-149	1.80E-02	2.41E-02
Eu-150	2.38E+01	3.19E+01
Eu-150m	6.89E-04	9.23E-04
Eu-150m+D	6.89E-04	9.23E-04
Eu-152+D	9.91E+00	1.33E+01
Eu-152m+D	1.26E-03	1.69E-03
Eu-152n+D	2.20E-04	2.95E-04
Eu-152n	8.89E-05	1.19E-04
Eu-154	7.62E+00	1.02E+01
Eu-154m+D	1.34E-04	1.80E-04
Eu-154m	5.84E-05	7.85E-05
Eu-155	2.39E-01	3.20E-01
Eu-156	7.08E-02	9.48E-02
Eu-157	1.58E-03	2.12E-03
Gd-148	4.09E+01	5.47E+01
Gd-149+D	1.77E-02	2.36E-02
Gd-150+D	3.83E+01	5.12E+01
Gd-151+D	2.69E-02	3.60E-02
Gd-152	2.95E+01	3.95E+01
Gd-153	6.75E-02	9.04E-02
Gd-159	9.71E-04	1.30E-03
Tb-157	8.77E-02	1.18E-01
Tb-158	1.84E+01	2.47E+01
Tb-160	2.42E-01	3.24E-01
Tb-161	5.56E-03	7.45E-03
Dy-159	1.76E-02	2.35E-02
Dy-165	2.13E-04	2.85E-04
Dy-169+D	Er-169	Er-169
Ho-163	4.72E-04	6.32E-04
Ho-164	3.77E-05	5.07E-05
Ho-164m+D	5.99E-05	8.03E-05
Ho-164m	5.34E-05	7.18E-05
Ho-166	2.28E-03	3.05E-03
Ho-166m	4.17E+01	5.58E+01
Er-169	4.09E-03	5.47E-03
Er-171+D	1.25E-03	1.68E-03
Tm-168	3.06E-01	4.10E-01
Tm-170	5.63E-02	7.55E-02
Tm-171	7.98E-03	1.07E-02
Yb-164+D	8.76E-04	1.16E-03
Yb-164	1.59E-04	2.14E-04
Yb-165+D	2.26E-04	3.08E-04
Yb-166+D	1.33E-02	1.78E-02
Yb-166	2.66E-03	3.56E-03
Yb-167+D	1.97E-04	2.67E-04
Yb-169	4.17E-02	5.58E-02
Yb-175	2.48E-03	3.32E-03
Yb-177+D	4.30E-04	5.76E-04
Lu-172	3.00E+00	4.02E+00
Lu-172m+D	1.37E-05	1.83E-05
Lu-172m	3.51E-10	4.88E-10
Lu-173	2.18E-01	2.92E-01
Lu-177	4.47E-03	5.98E-03
Lu-177m+D	4.49E-01	6.01E-01
Hf-172+D	2.36E-01	3.17E-01
Hf-175	6.75E-02	9.04E-02
Hf-177m	2.42E-03	3.25E-03
Hf-178	Hf-178m	Hf-178m
Hf-178m	3.16E+01	4.24E+01
Hf-179m	7.76E-02	1.04E-01
Hf-180m	1.82E-03	2.44E-03
Hf-181	8.18E-02	1.10E-01
Hf-182+D	3.90E+01	5.22E+01
Hf-182	6.62E+00	8.87E+00
Ta-179	3.54E-02	4.74E-02
Ta-180	1.89E-04	2.53E-04
Ta-182	3.87E-01	5.18E-01
Ta-182m+D	2.71E-04	3.66E-04
Ta-182m	2.37E-04	3.21E-04
Ta-183	1.05E-02	1.41E-02
W-181	2.07E-02	2.77E-02
W-185	4.49E-02	6.01E-02
W-185m+D	3.06E-06	4.34E-06
W-185m	2.48E-06	3.57E-06
W-187+D	2.60E-03	3.48E-03
W-188+D	2.23E-01	2.99E-01
W-188	1.97E-01	2.64E-01
Re-183	6.23E-02	8.35E-02
Re-186	4.37E-03	5.85E-03
Re-186m+D	2.29E+00	3.08E+00
Re-186m	1.10E+00	1.48E+00
Re-187	1.53E-03	2.06E-03
Re-188	1.94E-03	2.60E-03
Os-185	1.67E-01	2.24E-01
Os-191	1.12E-02	1.50E-02
Ir-189+D	4.96E-03	6.64E-03
Ir-190	5.15E-02	6.90E-02
Ir-192	1.83E-01	2.46E-01
Ir-194	2.04E-03	2.73E-03
Pt-191	3.12E-03	4.18E-03
Pt-193	4.61E-03	6.17E-03
Pt-193m+D	2.75E-03	3.69E-03
Pt-195m	3.82E-03	5.12E-03
Pt-197	1.01E-03	1.35E-03
Pt-197m+D	2.84E-04	3.80E-04
Pt-199+D	2.67E-04	3.59E-04
Pt-199m+D	Pt-199+D	Pt-199+D
Au-193+D	6.88E-04	9.21E-04
Au-193m+D	4.22E-08	5.65E-08
Au-193m	1.89E-15	3.60E-15
Au-194	5.48E-03	7.34E-03
Au-195	4.35E-02	5.83E-02
Au-195m+D	3.88E-07	5.69E-07
Au-195m	3.05E-07	4.58E-07

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
Au-196	8.88E-03	1.19E-02
Au-196m+D	2.09E-03	2.79E-03
Au-196m	1.64E-03	2.19E-03
Au-198	5.51E-03	7.37E-03
Au-198m+D	1.02E-02	1.37E-02
Au-198m	7.89E-03	1.06E-02
Au-199	2.83E-03	3.78E-03
Hg-203	4.53E-02	6.07E-02
Hg-205	7.32E-06	1.01E-05
Hg-206+D	8.57E-05	1.17E-04
Tl-200	5.17E-03	6.92E-03
Tl-201	1.20E-03	1.61E-03
Tl-202	1.87E-02	2.50E-02
Tl-204	2.04E-01	2.73E-01
Tl-206	4.05E-06	5.61E-06
Tl-206m	9.64E-04	1.34E-03
Tl-207+D	5.15E-06	7.11E-06
Tl-208	1.21E-03	1.70E-03
Tl-209+D	4.69E-04	6.66E-04
Tl-210+D	2.21E-04	3.22E-04
Pb-203	2.45E-03	3.28E-03
Pb-204m	2.26E-03	3.03E-03
Pb-205	1.30E-02	1.75E-02
Pb-209	1.55E-04	2.07E-04
Pb-210+D	2.05E+01	2.75E+01
Pb-211+D	3.07E-02	4.14E-02
Pb-212+D	4.46E-01	5.96E-01
Pb-214+D	3.69E-02	4.93E-02
Pb-214	3.09E-02	4.16E-02
Bi-207	2.22E+01	2.97E+01
Bi-208	6.09E+01	8.15E+01
Bi-210+D	2.58E-01	3.45E-01
Bi-210m+D	1.96E+01	2.63E+01
Bi-211+D	1.18E-05	1.66E-05
Bi-211	9.35E-06	1.33E-05
Bi-212+D	7.66E-02	1.02E-01
Bi-212n+D	6.49E-05	8.86E-05
Bi-212n	5.66E-06	7.74E-06
Bi-213+D	7.25E-02	9.75E-02
Bi-214+D	3.37E-02	4.55E-02
Po-208+D	2.19E+01	2.93E+01
Po-209+D	2.35E+01	3.14E+01
Po-210	1.58E+01	2.12E+01
Po-211	0.00E+00	0.00E+00
Po-212	0.00E+00	0.00E+00
Po-212m	1.07E-06	1.59E-06
Po-213+D	0.00E+00	0.00E+00
Po-214+D	4.82E-12	6.46E-12
Po-215+D	2.53E-08	3.40E-08
Po-215	1.67E-24	2.23E-24
Po-216+D	1.69E-06	2.25E-06
Po-216	1.38E-23	1.83E-23
Po-218+D	2.79E-03	3.65E-03
Po-218	1.91E-11	2.68E-11
At-211+D	2.71E-01	3.62E-01
At-217+D	8.56E-07	1.15E-06
At-217	0.00E+00	0.00E+00
At-218+D	4.24E-05	5.72E-05
At-218	2.46E-21	4.71E-21
Rn-218+D	1.02E-09	1.38E-09
Rn-218	9.25E-29	4.06E-29
Rn-219+D	5.64E-05	7.58E-05
Rn-219	5.11E-15	6.87E-15
Rn-220+D	6.29E-04	8.39E-04
Rn-220	1.72E-08	2.54E-08
Rn-222+D	1.83E-03	2.24E-03
Rn-222	3.83E-07	5.11E-07
Rn-224+D	Fr-224+D	Fr-224+D
Fr-221+D	4.05E-03	5.27E-03
Fr-221	1.37E-05	1.89E-05
Fr-222+D	5.41E-02	7.32E-02
Fr-223+D	2.79E-02	3.73E-02
Fr-223	2.40E-02	3.23E-02
Fr-224+D	3.38E-03	4.42E-03
Fr-224	2.07E-04	2.89E-04
Ra-223+D	2.01E+01	2.70E+01
Ra-224+D	7.83E+00	1.05E+01
Ra-225+D	1.76E+01	2.36E+01
Ra-226+D	7.24E+01	9.70E+01
Ra-226	2.68E+01	3.59E+01
Ra-227+D	1.10E-03	1.48E-03
Ra-228+D	4.17E+01	5.59E+01
Ra-228	3.21E+01	4.30E+01
Ac-225+D	1.97E+01	2.64E+01
Ac-226+D	3.06E+00	4.10E+00
Ac-227+D	2.65E+02	3.55E+02
Ac-228+D	3.87E-02	5.18E-02
Th-227+D	2.79E+01	3.74E+01
Th-228+D	1.25E+02	1.68E+02
Th-229+D	2.67E+02	3.58E+02
Th-230+D	5.30E+01	7.10E+01
Th-231+D	9.32E-04	1.25E-03
Th-232+D	1.43E+02	1.91E+02
Th-232	9.39E+01	1.26E+02
Th-233+D	8.93E-05	1.01E-04
Th-233	7.99E-05	1.08E-04
Th-234+D	6.21E-02	8.32E-02
Th-234	5.52E-02	7.39E-02
Pa-231+D	3.53E+02	4.72E+02
Pa-232+D	7.95E-03	1.06E-02
Pa-232	6.60E-03	8.83E-03
Pa-233+D	3.32E-02	4.45E-02
Pa-234+D	3.29E-03	4.40E-03
Pa-234m+D	1.80E-06	2.63E-06
U-232+D	5.86E+01	7.83E+01
U-232	3.27E+01	4.37E+01
U-233+D	1.14E+01	1.52E+01
U-234+D	1.11E+01	1.49E+01
U-235+D	1.44E+01	1.93E+01
U-235m+D	1.86E-09	2.50E-09
U-236+D	1.02E+01	1.36E+01
U-237+D	8.26E-03	1.11E-02
U-238+D	1.26E+01	1.69E+01
U-238	9.25E+00	1.24E+01
U-239+D	1.07E-04	1.43E-04
U-240+D	2.20E-03	2.93E-03

Nuclide or Decay Chain [a,b]	MPR Dose Factor [c] (mrem/yr per Ci/yr)	MA Dose Factor [c] (mrem/yr per Ci/yr)
U-240	1.52E-03	2.03E-03
Np-235	4.90E-03	6.56E-03
Np-236	2.19E+01	2.94E+01
Np-236m+D	1.80E-02	2.40E-02
Np-237+D	8.88E+01	1.18E+02
Np-238+D	1.06E-02	1.42E-02
Np-239+D	3.78E-03	5.08E-03
Np-240+D	1.26E-03	1.69E-03
Np-240m+D	2.05E-04	2.81E-04
Pu-234+D	5.54E-02	7.42E-02
Pu-235+D	7.29E-05	9.82E-05
Pu-236+D	7.04E+01	9.42E+01
Pu-237+D	7.33E-03	9.82E-03
Pu-238+D	1.66E+02	2.23E+02
Pu-239+D	1.81E+02	2.43E+02
Pu-240+D	1.81E+02	2.43E+02
Pu-241+D	3.41E+00	4.56E+00
Pu-242+D	1.72E+02	2.31E+02
Pu-243+D	2.60E-04	3.48E-04
Pu-244+D	1.80E+02	2.41E+02
Pu-246+D	5.42E-02	7.26E-02
Pu-246	2.80E-02	3.75E-02
Am-240+D	7.44E-03	9.96E-03
Am-241+D	1.50E+02	2.01E+02
Am-242+D	5.00E-02	6.69E-02
Am-242m+D	1.35E+02	1.81E+02
Am-243+D	1.53E+02	2.06E+02
Am-244+D	8.25E-03	1.10E-02
Am-244m+D	3.01E-04	4.02E-04
Am-244m	2.69E-04	3.62E-04
Am-245+D	1.83E-04	2.45E-04
Am-246+D	8.82E-04	1.19E-03
Cm-241+D	1.56E-01	2.09E-01
Cm-242+D	1.51E+01	2.03E+01
Cm-243+D	1.14E+02	1.53E+02
Cm-244+D	9.39E+01	1.26E+02
Cm-245+D	1.55E+02	2.07E+02
Cm-246+D	1.52E+02	2.04E+02
Cm-247+D	1.48E+02	1.98E+02
Cm-248+D	5.80E+02	7.77E+02
Cm-249+D	1.27E-04	1.70E-04
Cm-250+D	4.05E+03	5.41E+03
Bk-247+D	2.55E+02	3.41E+02
Bk-248m+D	5.62E-02	7.53E-02
Bk-249+D	6.30E-01	8.43E-01
Bk-250+D	4.65E-03	6.23E-03
Cf-249+D	2.61E+02	3.50E+02
Cf-250+D	1.21E+02	1.61E+02
Cf-251+D	2.61E+02	3.49E+02
Cf-252+D	6.86E+01	9.18E+01
Es-253+D	7.33E+00	9.81E+00
Es-254+D	2.75E+01	3.68E+01

Notes:

(a) +D indicates that the listed radionuclide dose includes contribution from the parent radionuclide plus decay products grown in during transit and build-up period. If nuclide +D is followed by the nuclide without +D, the decay chain members contribute greater than 10% of the nuclide+D dose.

(b) V = vapor; E = elemental; O = organic compounds; F = particulate, fast clearance rate; M = particulate, moderate clearance rate; S = particulate, slow clearance rate. Carbon isotopes are modeled as particulate (M), carbon monoxide (CO), or carbon dioxide (CO_2).

(c) If a radionuclide is indicated rather than a dose factor value, the nuclide is used as a surrogate. A surrogate is required when the nuclide (or specific chemical form) in the first column is not available in CAP88-PC V4.1.1. See Table 3.3 for additional details.

Shaded cells indicate nuclides that are new to this document. Either they 1) are available in CAP88-PC Version 4.1.1, but were not available in CAP88-PC Version 4.0; 2) are a new nuclide authorized for release from a PNNL Richland facility; 3) are new to consider as a surrogate for another nuclide in the list; OR 4) are newly indicated parent-only nuclides as indicated in Table 3.2.

3.5 PTE Dose Estimation Using LMFs

A method was presented in Section 3.4 of Snyder, Hay, and Barnett (2016) to determine PTE dose factors at alternative campus source locations that have lower levels of radioactive air emissions than the PSF. This method uses the tabulated PSF unit dose factors along with a multiplier. In the past, this method was applied to emissions from a facility at the southern PNNL-Richland campus. No such facility currently exists, but the method could be applied at future facilities, which will be referred to here as "LP Facility" for Low-PTE Facility.

The MPR and MA locations for a hypothetical Low-PTE Facility are determined in the same manner as was done for PSF. In future revisions of this document Location Modification Factors (LMFs) for all MPR and MA location would be tabulated in Appendix A. An LMF for the MPR and the MA is determined and can be applied as a multiple to the Table 3.6 values. LMFs vary by receptor location (MPR or MA), emission source (LP Facility), and nuclide type (gas, iodine, or particulate). This method works when receptor distances are similar for a given receptor type, but may fail for very short-lived nuclides with large (greater than about 1 km) differences in receptor distance. This failure is due to the significant decay during transport to a much longer distance-to-receptor. In the event of such a failure, the use of an LMF must be abandoned and a full assessment of unit-dose factors would need to be determined for the LP Facility (Snyder and Barnett 2017).

The LMF is the ratio of air concentration for the facility of interest and that of the Campus location (i.e., the PSF) with dose-per-unit-release dose factors. The air concentration measure (X/Q value) for each emission location/emission type/receptor type is determined by CAP88 modeling. PSF X/Q values are provided in Appendix A. For a given emission type, the difference in dispersion results from the combined consideration of distances and direction to offsite locations relative to the emission location (see example for MPR below; Eq. 3.1) and site meteorology. The emission types considered are gases, iodines, particulates, and radon emissions. The LMF may differ for each emission type. Gases include H, Ne, Ar, Kr, Xe, and Rn isotopes; iodines and radons are self-explanatory; and the remainder are particulates.

$$LMF_{b,t\,(MPR)} = C_{b,t\,(MPR)} \div C_{Campus,t\,(MPR)} \qquad \text{(Eq. 3.1)}$$

Where $LMF_{b,t\,(MPR)}$ = MPR location modification factor for facility b and emission type t (unitless),
b = facility b (LP facility),
t = gas, iodine, and particulates (represented by H-3 vapor, I-129, and Pu-239, respectively),
$C_{b,t\,(MPR)}$ = air concentration measure (X/Q) for the MPR of facility b for emission type t (Ci/m^3 per Ci/sec), and
$C_{Campus,t\,(MPR)}$ = air concentration measure (X/Q) for the MPR of PNNL-Richland campus for emission type t (Ci/m^3 per Ci/sec).

The MA location LMF determination and dose calculations can be done in the same manner as that of Eq. 3.1 and 3.2, with MA data replacing MPR data. See Appendix A for the MA air concentration measures for each emission location/emission type.

As an example, a fictional LP Facility is assumed to be located on the west side of the PNNL-Richland campus at the intersection of Horn Rapids Rd and Stevens Drive. The MPR for this

facility would be located at the offsite business (a warehouse) SSW of the fictional LP Facility. The X/Q values for such a facility are determined. The MPR LMFs for the LP Facility emission units, calculated as in Eq. 3.1, are indicated in Table 3.7. The LP Facility MPR is 580 m SSW of the LP Facility and the PNNL-Richland campus MPR is 640 m SSE of PSF. The LMF values indicate that the dispersion to the warehouse receptor is about half that of the PSF MPR.

Table 3.7. Location Modification Factors for LP Facility

Nuclide Release	LP Facility $LMF_{(MPR)}$
Gas, Particulate, Radon	0.4
Iodine	0.6

Eq. 3.2 indicates how a dose to the MPR for the LP Facility is calculated. A similar method can be used for the MA location dose determination, if the MA receptor differs from the MPR location. For purposes of permitting, use of an MPR location modification factor ($LMF_{(MPR)}$) allows the dose to the LP Facility's MPR to be readily calculated from the PNNL-Richland campus MPR dose-per-unit-release factors listed in Table 3.6. Eqs. 3.3 and 3.4 provide an example for a Sr-90 emission from the hypothetical LP Facility.

$$D_{b,n\,(MPR)} = A_{b,n} * LMF_{b,t\,(MPR)} * F_{n,Campus\,(MPR)} \qquad \text{(Eq. 3.2)}$$

Where $D_{b,n\,(MPR)}$ = dose to the MPR receptor of facility b for nuclide n (mrem/yr),
$A_{b,n}$ = activity of nuclide n emitted from facility b (Ci/yr),
b = facility b (LP Facility),
$LMF_{b,t\,(MPR)}$ = MPR location modification factor of facility b for emission type t (unitless),
t = gas, iodine, particulate, or radon emission, and
$F_{n,Campus\,(MPR)}$ = dose-per-unit-release factor for nuclide n (+D, if applicable) for the Richland campus MPR (mrem/yr per Ci/yr) (see Table 3.6).

$$D_{\text{LP Facility,Sr-90 MPR}} = (\text{Ci Sr-90 from LP facility}) * (F_{\text{Sr-90+D,Campus (MPR)}}) * (LMF_{\text{LP Facility,particulate (MPR)}}) \qquad \text{(Eq. 3.3)}$$

$$2.1\text{E-}6 \text{ mrem/yr} = (4.1\text{E-}7 \text{ Ci/yr Sr-90}) * (1.31\text{E+}01 \text{ mrem/yr per Ci/yr}) * (0.4) \qquad \text{(Eq. 3.4)}$$

4.0 PNNL-Sequim Campus PTE

The methods used to estimate emissions (Section 2.0) are the same for both PNNL campuses. However, the method used to estimate dose differs. The Sequim facility uses COMPLY modeling, whereas the Richland facility uses CAP88-PC modeling. COMPLY is appropriate software to use for the lower levels of emissions from the Sequim facility, as it is designed to be easy to run and requires only minimum input. The calculations for this document use COMPLY Version 1.7.1 (EPA 1989). COMPLY modeling is based on screening assessments with four levels of complexity. The highest level (Level 4) of complexity is currently implemented for the PNNL-Sequim campus, although all levels are options. COMPLY provides a conservative (overestimated) dose result for Sequim public receptors for a somewhat limited set of radionuclides. As a screening model, if emissions modeling resulted in an MPR dose greater than the 10 mrem/yr standard, the dose assessment could be refined by modeling in CAP88-PC for a more precise dose estimate.

4.1 Estimating Dose from Potential Emissions

COMPLY Version 1.7.1 internal and external dosimetry is based on ICRP 26/30 (ICRP 1977, 1979). External dose factors are based on DOE 1988. Environmental modeling (soil, plant, and animal) models are from NCRP 1989. COMPLY reports dose as mrem total effective dose equivalent with no organ doses provided.

4.2 Parameters and Data Used to Demonstrate Compliance

The Sequim facility is located in the Puget Sound in what can be described as a meteorological backwater. The facility is on the eastern side of Washington's Olympic peninsula, in the rain shadow of Mount Olympus. Average annual wind speeds are lower than the COMPLY default of 2.0 m/s (4.5 mph).

COMPLY can be run at Levels 1-4. PNNL-Sequim campus compliance may be demonstrated using Level 1 or 4. Level 1 would indicate exemption from dose determinations because onsite possession quality (Ci/yr) are below the values in 40 CFR Part 61, Appendix E, Table 1, "Annual Possession Quantities for Environmental Compliance." Level 4 provides dose factors for the most detailed analysis. COMPLY Level 4, with a wind rose and a unit release (1 Ci/yr) of the nuclides are modeled to obtain unit-release dose factors for specific nuclides. To the extent possible, lung absorption fractions are assigned in accordance with Appendix B with the available older terminology (D, W, Y) assigned for the current terminology (F, M, S, respectively).

Table 4.1 provides COMPLY input assumptions for the public receptors. Table 4.2 provides the distances in each direction to actual receptors (potential MPR and MA locations). The MPR location determined for the dose factors in Section 4.3 is 234 m west of the central release location. The MA location determined is on the shoreline east of the release point, due to the predominance of westerly winds.

Radiological operations at the PNNL-Sequim campus are very limited and estimated MEI dose impacts are many orders of magnitude below the dose standard. As a result, two simplifications are introduced for Sequim campus dose factors. First, the most recent 5 years of compliance reports indicate that the MA dose was at most 12 times the MEI dose estimate. As a result, PTE dose factors for the MA

receptor are not presented in this document. (If radiological air emissions greatly increase at the PNNL-Sequim campus, the ERT lead should consider revising this document to present MPR PTE dose factors.) Table 4.1 and Table 4.2 provide the input data to perform the calculations. Second, the full set of radionuclides evaluated is much more limited. For radionuclide emissions that are NOT included in Table 4.3 (radionuclides), the generic alpha emitter or generic beta/gamma emitter MPR dose factor should be assigned (respectively, Am-241 and Cs-137). If results from use of Am-241 or Cs-137 are considered too overestimating, the assessor can refer to surrogate nuclides authorized for the PNNL-Richland campus (see Table 3.6) or otherwise seek permission for the use of other alternatives.

Table 4.1. Inputs and Assumptions of PNNL- Sequim Campus MPR and MA Dose-per-Unit-Release Factor Calculations

Parameter	MPR J-MSL Value (Level 4 with wind rose)	MA J-MSL Value (Level 4, NWR)[(a)]
Nuclide names	<varies>	<varies>
Concentrations (Ci/m^3)	NA	NA
Annual possession amount (Ci)	NA	NA
Release rates (Ci/yr *or* Ci/s)	1 Ci/year	1 Ci/year
Release height (m)	5 m	5 m
Building height (m)	5 m	5 m
Stack or vent diameter (m)	NA	NA
Volumetric flow rate (m^3/s)	NA	NA
Distance from source-to-receptor (m)	NA	TBD [(c)]
Source and receptor on same building?	N	N
Input wind rose?	Y	NA
Building width (m)	5 m	5 m
Building length (m)	5 m	NA (NWR)
Stack distances from file?	Y <enter and save to file>	NA
Wind speed (m/s) – default value	NA	2.0 m/s[(b)]
Distances to sources of food production (m)	NA	230 m[(c)]
Stack temperature (°F)	NA	NA
Ambient air temperature (°F)	NA	NA
Wind rose	<enter and save to file>	NA(NWR)

NA = not applicable. NA(NWR) = not applicable because NWR data is used. To convert to feet, multiply meters by 3.28.

(a) The no wind rose (NWR) option is used only as a default when meteorological information is unusable or a conservative (over-estimated) result is acceptable.

(b) Conservative value relative to the average wind speed for closest receptors.

(c) Smallest potential distance. MPR receptor location would be determined by COMPLY and boundary distance table (see Table 4.2).

Table 4.2. PNNL-Sequim Campus Potential Receptor Locations and Distances to Boundary

Direction from Central Campus	Smallest Distance to a Potential MPR Location	Smallest Distance to the Campus Boundary Potential MA Location
N	1,834 m, res	319 m
NNE	30,670 m, busi	211 m
NE	10,000 m, busi	147 m
ENE	1,877 m, res	129 m
E	1,979 m, res	131 m
ESE	2,678 m, res	154 m
SE	3,693 m, res	176 m
SSE	1,532 m, busi	474 m
S	720 m, res	291 m
SSW	723 m, res	230 m
SW	340 m, res	95 m
WSW	276 m, res	81 m
W	234 m, res	80 m
WNW	230 m, res	81 m
NW	1,261 m, busi	96 m
NNW	840 m, res	220 m

Central Campus point and PNNL-Sequim campus boundary (see Figure 1.2).
Blue shading = a conservative shore location where no member of the public could occupy 24/7 and not the farther out tideland boundary location.
res = residential structure.
busi = business (NNE and NE are parks on small-island parks; SSE is a marina park; NW is a sewage treatment plant).

4.3 Sequim Campus MPR Location Dose Factors

The PNNL-Sequim campus MPR dose-per-unit-release factors in Table 4.3 are used to estimate potential radiological dose from the PNNL-Sequim campus J-MSL emission unit for purposes of permitting. The doses are estimated using PTE release rates (Ci/yr) for dispersible radionuclides expected to be present in the facility, multiplied by corresponding values in Table 4.3, which indicate a dose (mrem TED) for a 1-Ci/yr release of each radionuclide. Doses for all radionuclides potentially released from the emission unit are combined to estimate the total annual MPR or MA PTE dose.

Many radionuclides decay into other radionuclides, creating a radioactive-decay chain consisting of a parent nuclide and its radioactive progeny (decay products, daughters). For COMPLY cases, the user must enter releases of progeny nuclides separately. As indicated in the user guide, the program automatically handles the ingrowth of progeny after the release of the parent. The Table 4.3 values assume release of 1 Ci/yr of the parent isotope with no other decay-chain members present initially.

Table 4.3 lists PNNL-Sequim campus dose-per-unit-release factors for the MPR location by radionuclide. The calculations were performed for a 1 Ci/yr release rate for each radionuclide. Dose factor values in the tables are calculated estimates to be used for all emission unit locations on the PNNL-Sequim campus and may be used for prospective estimates of radiation dose.

Isotopes not in the COMPLY v1.7.1 library and not already approved as a surrogate (e.g., see Table 3.6) would use the generic gross alpha or gross beta/gamma surrogate radionuclides (i.e., Am-241 and Cs-137). Any other non-generic gross alpha or gross beta/gamma surrogate radionuclides will be approved by the regulatory authority (WAC 246-247-035).

Multiple methods are available to prepare the dose-per-unit-release factors for isotopes that are not in the COMPLY Version 1.7.1 library, and the approaches used are listed in order of preference below. The method adopted for an unavailable nuclide in the prior version of this document was retained. Methods used to estimate dose for radionuclides not in the COMPLY library include the following:

- A chemically and radiologically similar isotope (i.e., same or related element, similar half-life, similar radiological decay mode) that should be conservative for the missing isotope was identified.
- Where the missing isotope has a metastable variant in the COMPLY database, the related isotope from the library was used because the beginning and end states, and the total decay energy, are generally the same.
- For very short-lived isotopes (i.e., the half-life is less than about 2 hours) that have complex decay chains, the first longer-lived decay product was used as the surrogate. The dose-per-unit-release factor for the surrogate was then adjusted to account for the quantity of surrogate that would result from the decay of 1 Ci of the parent isotope.

Where other options did not apply or were not viable, conservative isotope values of Cs-137 for beta/gamma emitters and Am-241 for alpha emitters were used. For total natural uranium measurements (U-234, U-235, and U-238), the U-235 dose factor might be applied for total uranium dose calculations for isotopic natural uranium. However, also consider that natural uranium radioactivity is approximately 49.2% U-234, 2.2% U-235, and 48.6% U-238 (NRC 2023).

Table 4.3. Maximum Public Receptor and Maximum Air Location Dose-per-Unit-Release Factors for the PNNL-Sequim campus (Central Emission Location)

Nuclide	Footnote	COMPLY V1.7.1 Solubility Class[a]	MPR[b] Dose Factor (234 m W receptor) (mrem EDE/yr per Ci/yr)
H-2	(c)	n/a	0
H-3		Vapor	0.00079
Li-6	(c)	n/a	0
Li-7	(c)	n/a	0
Fe-55		D	0.082
Ni-63	(d)	Vapor	0.071
Sr-90		Y	38.9
Tc-99		W	6.0
I-125		D	16.2
I-129		D	241.0
Cs-137	(e)	D	90.6
Pb-210	(f)	D	205.0
Po-210		D	103.0
Ra-226		W	592.0
Ra-228		W	113.0
Th-228		Y	1720.0
Th-232	(d)	W	8530.0
U-233		Y	687.0
U-234		Y	672.0
U-235		Y	676.0
U-238		Y	607.0
Np-237		W	2980.0
Pu-239		W	2190.0
Pu-241		W	42.3
Am-241	(e)	W	2270.0
Cm-244		W	1270.0

Bold font = alpha-emitting nuclides. All others are beta/gamma emitters.
EDE = effective dose equivalent.

(a) The lung solubility class in COMPLY version 1.7.1 follows ICRP 29/30 methodology. These solubility factors have been updated in ICRP 66 with new nomenclature (ICRP 1994). The COMPLY and its corresponding (updated) solubility class are D=F; W=M, and Y=S.

(b) Using 9-yr average meteorological data (2013-17, 2019-21, 2023), the MPR receptor COMPLY identified was 234 m W of the Central Campus release location, which happens to be the same as the closest potential residence, business, or farm location.

(c) Isotope entered for safeguards information, only, in the database.

(d) Th-232: Solubility class S is preferred, but the default class W used is an overestimating assumption. Ni-63: Solubility class W is preferred, but the default class V (vapor) used is an overestimating assumption.

(e) Am-241 is the default alpha-emitting nuclide. Cs-137 is the default beta/gamma emitting nuclide for isotopes not individually listed in the table.

(f) The solubility class listed is the only available option in COMPLY v1.7.1.

5.0 Quality Assurance

This section discusses quality assurance (QA) aspects of determining dose-per-unit-release rates for the PNNL-Richland campus. An approved technical review checklist for the PNNL-Richland campus dose-per-unit-release calculations is also provided in Section 6.0.

PNNL QA requirements for sampling and analyzing radiological emissions are outlined in EM-QA-01, *Effluent Management Quality Assurance Plan* (PNNL 2024). This plan outlines the sampling requirements for the emission unit as well as agreements with PNNL Facilities and Operations to verify that sampling systems and radiological exhaust systems are adequately maintained. The effluent monitoring and QA programs described by the plan are based on one or more of the following documents:

- 10 CFR Part 830, "Nuclear Safety Management" (DOE 2001)
- DOE Order 414.1D, *Quality Assurance*, "Contractor Requirements Document" (DOE 2020)
- 40 CFR Part 61, "Protection of the Environment/National Emission Standards for Hazardous Air Pollutants (NESHAP), Appendix B, Method 114," Test Methods for Measuring Radionuclide Emissions from Stationary Sources, Part 4, Quality Assurance Methods
- DOE Order 458.1, *Radiation Protection of the Public and the Environment* (DOE 2025)
- DOE HDBK-1216-2015, *Environmental Radiological Effluent Monitoring and Environmental Surveillance* (DOE 2022a)
- *EPA Requirements for Quality Assurance Project Plans* (QA/R-5; EPA 2001).

Dose-per-unit-release estimates for the PNNL-Richland campus and the PNNL-Sequim campus were reviewed. Reports that contain technical analyses are reviewed internally at PNNL by subject matter experts, editorial staff, and management. PNNL also conducts periodic management and QA self assessments of internal projects, commensurate with the level of risk and potential implications for public health associated with those projects. A technical review checklist for the PNNL-Richland campus radiological dose calculations are attached (Section 6.0).

6.0 Technical Review Checklists

PNNL-Richland campus Technical Review Checklist

TECHNICAL REVIEW CHECKLIST

List of Prior Report:
SF Snyder and JM Barnett July 2016. *PNNL Dose-per-Unit-Release Factors For Calculating Radionuclide Emissions Potential-to-Emit Doses*, PNNL-17847, Rev. 4.

Document reviewed (include e.g. title or description of calculation, doct number, author, and date):
SF Snyder, TR Hay, and JM Barnett. 2025. *PNNL Dose-per-Unit-Release Factors for Calculating Radionuclide Emissions Potential-to-Emit Doses, PNNL-Richland and PNNL-Sequim campuses*, PNNL-17847, Rev. 5. – **Limited to the PNNL-Richland Campus dose modeling sections**

Description of update:
PNNL-17847, Rev. 5 updates the PNNL-Richland campus CAP88-PC modeling from Version 4.0 (2015) to Version 4.1.1 (2020). Updated meteorology (2014-2023) was used in the modeling. Unit-release dose factors were updated with CAP88-PC Version 4.1.1 model results. Additional nuclides permitted to be released from PNNL but not available with CAP88-PC v4.1.1 are documented. Both Maximum Public Receptor (MPR) dose factors and Maximum Air (MA) dose factors are included for the Richland campus. The MPR receptor location was changed from 530m SSE to 640m SSE. The MA receptor location was changed from 500m NW to 580m NW.
New to this revision are unit-release dose factors for the PNNL-Sequim campus. The limited number of dose factors provided were modeled with COMPLY version 1.7.1. Site-specific meteorology was used in the modeling. Only MPR unit-release-dose-factors are provided for the PNNL-Sequim campus. Modeling with COMPLY and one receptor's (only MPR) dose factors resulted from the limited radiological operations on the Sequim campus.
A discussion of the Location Modification Factor (LMF) calculation for assessing PNNL-Richland campus potential-to-emit-doses for any future radiological facility NOT in the PSF area is included. There are currently no such facilities since LSLII and RTL facilities' radiological operations ended.

Preparer: TR Hay 5/29/2025
Reviewer: SF Snyder 5/29./2025
Scope of Review: Calculations of radiological dose per unit release rate for the PTE receptors (maximally exposed member of the public) from radiological air effluents **at the PNNL-Richland campus**.

YES	NO*	N/A	
[X]	[ ]	[ ]	1. A technical review and approval of the environmental transport and dose calculation portion of the analysis has been performed and documented.
[X]	[ ]	[ ]	2. Technical review(s) and approval(s) of scenario and release determinations have been performed.
[X]	[ ]	[ ]	3. Appropriate computer software was used.
[X]	[ ]	[ ]	4. Receptor locations were appropriate for purpose of analysis.
[X]	[ ]	[ ]	5. All applicable environmental pathways and code options were included and were appropriate for the calculations.
[X]	[ ]	[ ]	6. PNNL campus data were used as applicable.
[ ]	[ ]	[X]	7. Any external adjustments to computer software output were justified and performed correctly.
[X]	[ ]	[ ]	8. The analysis is consistent with recommendations (e.g., EMP DAG).
[X]	[ ]	[]	9. Supporting notes, calculations, comments, comment resolutions, or other Information is attached.
[ ]		[X]	10. Substantive comments have been resolved.

Sandra F Snyder Digitally signed by Sandra F Snyder Date: 2025.05.29 15:19:05 -07'00'
Technical Reviewer (Sign and Date)

COMMENTS (add additional signed and dated pages if necessary):
The correct average temperature and precipitation rate was not used in the CAP88 cases (PTEr4 values run =12.0 C and 17.1 cm/y whereas the 2014-23 met-yrs values are 12.9C and 17.2 cm/yr). The reviewer re-ran 5 cases for each receptor (MPR and MA) and evaluated the X/Q for H3, Pu-239, I-129, and Rn-222 (cases 2,3,6,11) and also the unit-dose-factors for these cases were ratio'd to determine the impact to results when using the correct meteorological data. The greatest difference was 0.9% - a <1% difference – the ratios were largely 1.000 -- so the preparer will not be asked to re-run all cases and update the spreadsheets. Set 19 (a representative "new-to-r5" nuclide set) was also re-run with X/Q and UDF differences determined with the updated results also insignificant. It would be OK to indicate in the report that a 12.9 C temp and 17.2 cm/yr precip rate was run in the cases (report Table 3.4) even though r4 data was used for these parameters.

PNNL-Sequim campus Technical Review Checklist

TECHNICAL REVIEW CHECKLIST

List of Prior Report:
SF Snyder and JM Barnett July 2016. *PNNL Dose-per-Unit-Release Factors For Calculating Radionuclide Emissions Potential-to-Emit Doses*, PNNL-17847, Rev. 4.

Document reviewed (include e.g. title or description of calculation, doct number, author, and date):
SF Snyder, TR Hay, and JM Barnett. 2025. *PNNL Dose-per-Unit-Release Factors for Calculating Radionuclide Emissions Potential-to-Emit Doses, PNNL-Richland and PNNL-Sequim campuses*, PNNL-17847, Rev. 5. – **Limited to the PNNL-Sequim campus dose modeling sections**

Description of update:
PNNL-17847, Rev. 5 updates the PNNL-Richland campus CAP88-PC modeling from Version 4.0 (2015) to Version 4.1.1 (2020). Updated meteorology (2014-2023) was used in the modeling. Unit-release dose factors were updated with CAP88-PC Version 4.1.1 model results. Additional nuclides permitted to be released from PNNL but not available with CAP88-PC v4.1.1 are documented. Both Maximum Public Receptor (MPR) dose factors and Maximum Air (MA) dose factors are included for the Richland campus. The MPR receptor location was changed from 530m SSE to 640m SSE. The MA receptor location was changed from 500m NW to 580m NW.

New to this revision are unit-release dose factors for the PNNL-Sequim campus. The limited number of dose factors provided were modeled with COMPLY version 1.7.1. Site-specific meteorology was used in the modeling. Only MPR unit-release-dose-factors are provided for the PNNL-Sequim campus. Modeling with COMPLY and one receptor's (only MPR) dose factors resulted from the limited radiological operations on the Sequim campus.

A discussion of the Location Modification Factor (LMF) calculation for assessing PNNL-Richland campus potential-to-emit-doses for any future radiological facility NOT in the PSF area is included. There are currently no such facilities since LSLII and RTL facilities' radiological operations ended.

Preparer: SF Snyder 5/28/2025
Reviewer: TH 6/11/2025
Scope of Review: Calculations of radiological dose per unit release rate for the PTE receptors (maximally exposed member of the public) from radiological air effluents **at the Sequim campus**.

YES	NO*	N/A	
[x]	[ ]	[ ]	1. A technical review and approval of the environmental transport and dose calculation portion of the analysis has been performed and documented.
[x]	[ ]	[ ]	2. Technical review(s) and approval(s) of scenario and release determinations have been performed.
[x]	[ ]	[ ]	3. Appropriate computer software was used.
[x]	[ ]	[ ]	4. Receptor locations were appropriate for purpose of analysis.
[x]	[ ]	[ ]	5. All applicable environmental pathways and code options were included and were appropriate for the calculations.
[x]	[ ]	[ ]	6. PNNL campus data were used as applicable.
[]	[ ]	[x]	7. Any external adjustments to computer software output were justified and performed correctly.
[ ]	[ ]	[x]	8. The analysis is consistent with recommendations (e.g., EMP DAG).
[x]	[ ]	[]	9. Supporting notes, calculations, comments, comment resolutions, or other Information is attached.
[x]		[ ]	10. Substantive comments have been resolved.

Tristan Hay Digitally signed by Tristan Hay Date: 2025.06.11 09:49:13 -07'00'

Technical Reviewer (Sign and Date)

COMMENTS (add additional signed and dated pages if necessary):

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Appendix A

MPR and MA Details

The maximum receptors (Maximum Public Receptor [MPR] and maximum air [MA]) location and air concentration measures (X/Q values using long-term meteorology are indicated in the Table A.1 and Table A.2. These X/Q values could be used in conjunction with results from future PNNL-Richland campus radioactive air effluent emission unit modeling to determine Location Modification Factors as described in Section 3.5.

Table A.1. MPR Locations and X/Q Values

Emission Point	MPR Location	X/Q Values (sec/m^3) [a]			
		Gas	Iodine	Particulate	Radon
PNNL-Richland campus (PSF)[b]	640m SSE	5.99E-6	4.48E-6	5.90E-6	5.99E-6
PNNL-Sequim campus[c]	234 m W	NA	NA	NA	NA

(a) Nuclide assumptions for modeling were: Gas as H-3 vapor; iodine as I-129; particulate as Pu-239; and radon as Rn-222.
(b) PNNL-Richland campus evaluation used 10-yr average meteorology (2014-2023).
(c) PNNL- Sequim campus evaluation used 9-yr average meteorology (2013-17, 2019-21, 2023). A continuous timeframe was not available due to data recording issues. COMPLY does not provide X/Q values in output.

Table A.2. Maximum Air (MA) Locations and X/Q Values

Emission Point	MA Location	X/Q Values (sec/m^3) [a]			
		Gas	Iodine	Particulate	Radon
PNNL-Richland campus (PSF) [b]	580 m NW	8.00E-6	6.16E-6	7.89E-6	8.00E-6
PNNL-Sequim campus[b]	NA	NA	NA	NA	NA

(a) Nuclide assumptions for modeling were: Gas as H-3 vapor; iodine as I-129; particulate as Pu-239; and radon as Rn-222.
(b) See Table A.1 for meteorology information.

Appendix B

FGR13 Absorption Type Default Assumptions for CAP88-PC

Table B.1. Default FGR-13 Absorption Types and Particle Sizes to Apply (CAP88-PC 4.1.1)

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
H-3 (V)	V	0
H-3 (E)	G	0
H-3 (O)	G	0
H-3 (F)	F	1
H-3 (M)	M	1
H-3 (S)	S	1
Be-7	M	1
Be-10	M	1
C-11	M	1
C-11 (CO)	G	0
C-11 (CO2)	G	0
C-14	M	1
C-14 (CO)	G	0
C-14 (CO2)	G	0
C-15(c)	-	-
N-13	B	0
O-15	B	0
O-19	B	0
F-18	M	1
Na-22	M	1
Na-24	M	1
Na-24m (c)	-	-
Mg-27	B	0
Mg-28	M	1
Al-26	M	1
Al-28	B	0
Si-31	M	1
Si-32	M	1
P-32	M	1
P-33	M	1
S-35	M	1
Cl-36	M	1
Cl-38	M	1
Ar-37	B	0
Ar-39	B	0
Ar-41	B	0
Ar-42	B	0
K-40	M	1
K-42	M	1
Ca-41	M	1
Ca-45	M	1
Ca-47	M	1
Sc-44	M	1
Sc-44m	M	1
Sc-46	M	1
Sc-47	M	1
Sc-48	M	1
Ti-44	M	1
Ti-45	M	1
Ti-51	B	0
V-48	M	1
V-49	M	1
Cr-49	M	1
Cr-51	M	1
Cr-55	B	0
Mn-52	M	1
Mn-52m	M	1
Mn-53	M	1
Mn-54	M	1
Mn-56	M	1
Fe-55	M	1
Fe-59	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Co-56	M	1
Co-57	M	1
Co-58	M	1
Co-58m	M	1
Co-60	M	1
Co-60m	M	1
Ni-56	M	1
Ni-57	M	1
Ni-59	M	1
Ni-63	M	1
Ni-65	M	1
Ni-66	M	1
Cu-64	M	1
Cu-66	B	0
Cu-67	M	1
Zn-65	M	1
Zn-69	M	1
Zn-69m	M	1
Ga-67	M	1
Ga-68	M	1
Ga-70	M	1
Ga-72	M	1
Ga-73	M	1
Ge-68	M	1
Ge-69	M	1
Ge-71	M	1
Ge-71m (c)	-	-
Ge-73m (c)	-	-
Ge-75	M	1
Ge-77	M	1
Ge-77m (c)	-	-
As-73	M	1
As-74	M	1
As-76	M	1
As-77	M	1
Se-75	F	1
Se-77m	B	0
Se-79	F	1
Se-79m	B	0
Br-82	M	1
Br-82m	B	0
Br-83	M	1
Br-84	M	1
Br-84m	B	0
Br-85	B	0
Kr-81	B	0
Kr-81m	B	0
Kr-83m	B	0
Kr-85	B	0
Kr-85m	B	0
Kr-87	B	0
Kr-88	B	0

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Kr-89	*B*	0
Kr-90(c)	-	-
Rb-81	M	1
Rb-81m	M	1
Rb-82	B	0
Rb-82m	M	1
Rb-83	M	1
Rb-84	M	1
Rb-84m	M	1
Rb-86	M	1
Rb-86m	B	0
Rb-87	M	1
Rb-88	M	1
Rb-89	M	1
Rb-90	B	0
Rb-90m	B	0
Sr-82	M	1
Sr-83	M	1
Sr-85	M	1
Sr-85m	M	1
Sr-87m	M	1
Sr-89	M	1
Sr-90	M	1
Sr-91	M	1
Sr-92	M	1
Y-88	M	1
Y-89m	B	0
Y-90	M	1
Y-90m	M	1
Y-91	M	1
Y-91m	M	1
Y-92	M	1
Y-93	M	1
Zr-88	M	1
Zr-89	M	1
Zr-89m	B	0
Zr-93	M	1
Zr-95	M	1
Zr-97	M	1
Zr-98 (c)	-	-
Zr-99 (c)	-	-
Zr-100 (c)	-	-
Nb-91	M	1
Nb-91m	M	1
Nb-92	M	1
Nb-92m	M	1
Nb-93m	M	1
Nb-94	M	1
Nb-94m	B	0
Nb-95	M	1
Nb-95m	M	1
Nb-96	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Nb-97	M	1
Nb-97m	M	1
Nb-98 (c)	-	-
Nb-98m	M	1
Nb-99	B	0
Nb-100 (c)	-	-
Nb-101 (c)	-	-
Nb-103 (c)	-	-
Mo-93	M	1
Mo-93m	M	1
Mo-99	M	1
Mo-101	M	1
Mo-103 (c)	-	-
Mo-104 (c)	-	-
Mo-105 (c)	-	-
Tc-95	M	1
Tc-95m	M	1
Tc-96	M	1
Tc-96m	M	1
Tc-97	M	1
Tc-97m	M	1
Tc-98	M	1
Tc-99	M	1
Tc-99m	M	1
Tc-101	M	1
Tc-103 (c)	-	-
Tc-104	M	1
Tc-105	B	0
Tc-106 (c)	-	-
Ru-97	M	1
Ru-103	M	1
Ru-105	M	1
Ru-106	M	1
Rh-101	M	1
Rh-101m	M	1
Rh-102	M	1
Rh-102m	M	1
Rh-103m	M	1
Rh-104	B	0
Rh-104m	B	0
Rh-105	M	1
Rh-105m (c)	-	-
Rh-106	B	0
Pd-103	M	1
Pd-107	M	1
Pd-109	M	1
Pd-109m	B	0
Pd-111	M	1
Pd-112	M	1
Ag-105	M	1
Ag-106m	M	1
Ag-108	B	0
Ag-108m	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Ag-109m	B	0
Ag-110	B	0
Ag-110m	M	1
Ag-111	M	1
Ag-111m	B	0
Ag-112	M	1
Cd-107	M	1
Cd-109	M	1
Cd-111m	M	1
Cd-113	M	1
Cd-113m	M	1
Cd-115	M	1
Cd-115m	M	1
Cd-117	M	1
Cd-117m	M	1
Cd-119	B	0
In-106	B	0
In-111	M	1
In-111m	B	0
In-112	M	1
In-112m	M	1
In-113m	M	1
In-114	B	0
In-114m	M	1
In-115	M	1
In-115m	M	1
In-116 (c)	-	-
In-116m	M	1
In-117	M	1
In-117m	M	1
Sn-113	M	1
Sn-113m	M	1
Sn-117m	M	1
Sn-119m	M	1
Sn-121	M	1
Sn-121m	M	1
Sn-123	M	1
Sn-123m	M	1
Sn-125	M	1
Sn-125m	B	0
Sn-126	M	1
Sb-122	M	1
Sb-122m	B	0
Sb-124	M	1
Sb-124m	B	0
Sb-124n	M	1
Sb-125	M	1
Sb-126	M	1
Sb-126m	M	1
Sb-127	M	1
Sb-128	M	1
Sb-128m	M	1
Te-121	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Te-121m	M	1
Te-123	M	1
Te-123m	M	1
Te-125m	M	1
Te-127	M	1
Te-127m	M	1
Te-129	M	1
Te-129m	M	1
Te-131	M	1
Te-131m	M	1
Te-132	M	1
Te-132	M	1
Te-133	M	1
Te-133m	M	1
Te-134	M	1
I-122	B	0
I-122 (V)(c)	-	-
I-123	F	1
I-123 (V)	*V*	0
I-124	F	1
I-124(V)	*V*	0
I-125	F	1
I-125 (V)	*V*	0
I-126	F	1
I-126 (V)	*V*	0
I-128	F	1
I-128 (V)	*V*	0
I-129	F	1
I-129 (V)	*V*	0
I-130	F	1
I-130 (V)	*V*	0
I-130m	B	0
I-130m (V)(c)	-	-
I-131	F	1
I-131 (V)	*V*	0
I-132	F	1
I-132 (V)	*V*	0
I-132m	F	1
I-132m (V)	*V*	0
I-133	F	1
I-133 (V)	*V*	0
I-133m(c)	-	-
I-134	F	1
I-134 (V)	*V*	0
I-134m	B	0
I-134m (V) (c)	-	-
I-135	F	1
I-135 (V)	*V*	0
Xe-122	B	0
Xe-123	B	0
Xe-125	B	0
Xe-127	B	0
Xe-127m	B	0

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Xe-129m	B	0
Xe-131m	B	0
Xe-133	B	0
Xe-133m	B	0
Xe-135	B	0
Xe-135m	B	0
Xe-137	B	0
Xe-138	B	0
Xe-139 (c)	-	-
Cs-131	F	1
Cs-132	F	1
Cs-134	F	1
Cs-134m	F	1
Cs-135	F	1
Cs-135m	F	1
Cs-136	F	1
Cs-137	F	1
Cs-138	F	1
Cs-138m	B	0
Cs-139	B	0
Cs-140	B	0
Cs-141 (c)	-	-
Ba-131	M	1
Ba-131m	M	1
Ba-133	M	1
Ba-133m	M	1
Ba-135m	M	1
Ba-137m	B	0
Ba-139	M	1
Ba-140	M	1
Ba-141	M	1
Ba-142	M	1
Ba-143 (c)	-	-
La-137	M	1
La-138	M	1
La-140	M	1
La-141	M	1
La-142	M	1
La-143	M	1
La-144 (c)	-	-
Ce-139	M	1
Ce-141	M	1
Ce-142(c)	-	-
Ce-143	M	1
Ce-144	M	1
Pr-142	M	1
Pr-142m	M	1
Pr-143	M	1
Pr-144	M	1
Pr-144m	M	1
Nd-144	M	1
Nd-147	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Pm-143	M	1
Pm-144	M	1
Pm-145	M	1
Pm-146	M	1
Pm-147	M	1
Pm-148	M	1
Pm-148m	M	1
Pm-149	M	1
Pm-150	M	1
Pm-151	M	1
Sm-145	M	1
Sm-146	M	1
Sm-147	M	1
Sm-148	M	1
Sm-151	M	1
Sm-153	M	1
Sm-155	M	1
Sm-156	M	1
Sm-157	B	0
Eu-146	M	1
Eu-149	M	1
Eu-150	M	1
Eu-150m	M	1
Eu-152	M	1
Eu-152m	M	1
Eu-152n	M	1
Eu-154	M	1
Eu-154m	M	1
Eu-155	M	1
Eu-156	M	1
Eu-157	M	1
Gd-148	M	1
Gd-149	M	1
Gd-150	M	1
Gd-151	M	1
Gd-152	M	1
Gd-153	M	1
Gd-159	M	1
Tb-157	M	1
Tb-158	M	1
Tb-160	M	1
Tb-161	M	1
Dy-159	M	1
Dy-165	M	1
Dy-169 (c)	-	-
Ho-163	M	1
Ho-164	M	1
Ho-164m	M	1
Ho-166	M	1
Ho-166m	M	1
Er-169	M	1
Er-171	M	1
Tm-168	M	1
Tm-170	M	1
Tm-171	M	1
Yb-164	M	1
Yb-165	B	0
Yb-166	M	1
Yb-167	M	1
Yb-169	M	1
Yb-175	M	1
Yb-177	M	1
Lu-172	M	1
Lu-172m	B	0
Lu-173	M	1
Lu-177	M	1
Lu-177m	M	1
Hf-172	M	1
Hf-175	M	1
Hf-177m	M	1
Hf-178(c)	-	-
Hf-178m	M	1
Hf-179m	M	1
Hf-180m	M	1
Hf-181	M	1
Hf-182	M	1
Ta-179	M	1
Ta-180	M	1
Ta-182	M	1
Ta-182m	M	1
Ta-183	M	1
W-181	M	1
W-185	M	1
W-185m	B	0
W-187	M	1
W-188	M	1
Re-183	M	1
Re-186	M	1
Re-186m	M	1
Re-187	M	1
Re-188	M	1
Os-185	M	1
Os-191	M	1
Ir-189	M	1
Ir-190	M	1
Ir-192	M	1
Ir-194	M	1
Pt-191	M	1
Pt-193	M	1
Pt-193m	M	1
Pt-195m	M	1
Pt-197	M	1
Pt-197m	M	1
Pt-199	M	1
Pt-199m (c)	-	-
Au-193	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Au-193m	B	0
Au-194	M	1
Au-195	M	1
Au-195m	B	0
Au-196	M	1
Au-196m	M	1
Au-198	M	1
Au-198m	M	1
Au-199	M	1
Hg-203	M	1
Hg-205	B	0
Hg-206	B	0
Tl-200	M	1
Tl-201	M	1
Tl-202	M	1
Tl-204	M	1
Tl-206	B	0
Tl-206m	B	0
Tl-207	B	0
Tl-208	B	0
Tl-209	B	0
Tl-210	B	0
Pb-203	M	1
Pb-204m	M	1
Pb-205	M	1
Pb-209	M	1
Pb-210	M	1
Pb-211	M	1
Pb-212	M	1
Pb-214	M	1
Bi-207	M	1
Bi-208	M	1
Bi-210	M	1
Bi-210m	M	1
Bi-211	B	0
Bi-212	M	1
Bi-212n	B	0
Bi-213	M	1
Bi-214	M	1
Po-208	B	0
Po-209	M	1
Po-210	M	1
Po-211	B	0
Po-212	B	0
Po-212m	B	0
Po-213	B	0
Po-214	B	0
Po-215	B	0
Po-216	B	0
Po-218	B	0
At-111	M	1
At-217	B	0
At-218	B	0

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Rn-218	B	0
Rn-219	B	0
Rn-220	B	0
Rn-222	B	0
Rn-224(c)	-	-
Fr-221	B	0
Fr-222	M	1
Fr-223	M	1
Fr-224	B	0
Ra-223	M	1
Ra-224	M	1
Ra-225	M	1
Ra-226	M	1
Ra-227	M	1
Ra-228	M	1
Ac-225	M	1
Ac-226	M	1
Ac-227	M	1
Ac-228	M	1
Th-227	S	1
Th-228	S	1
Th-229	S	1
Th-230	S	1
Th-231	S	1
Th-232	S	1
Th-233	S	1
Th-234	S	1
Pa-231	M	1
Pa-232	M	1
Pa-233	M	1
Pa-234	M	1
Pa-234m	B	0
U-232	M	1
U-233	M	1
U-234	M	1
U-235	M	1
U-235m	M	1
U-236	M	1
U-237	M	1
U-238	M	1
U-239	M	1
U-240	M	1
Np-235	M	1
Np-236	M	1
Np-236m	M	1
Np-237	M	1
Np-238	M	1
Np-239	M	1
Np-240	M	1
Np-240m	B	0
Pu-234	M	1
Pu-235	M	1
Pu-236	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Pu-237	M	1
Pu-238	M	1
Pu-239	M	1
Pu-240	M	1
Pu-241	M	1
Pu-242	M	1
Pu-243	M	1
Pu-244	M	1
Pu-246	M	1
Am-240	M	1
Am-241	M	1
Am-242	M	1
Am-242m	M	1
Am-243	M	1
Am-244	M	1
Am-244m	M	1
Am-245	M	1
Am-246	M	1
Cm-241	M	1

Nuclide[a]	FGR-13 Absorption Type[a]	Particle size (micrometer)
Cm-242	M	1
Cm-243	M	1
Cm-244	M	1
Cm-245	M	1
Cm-246	M	1
Cm-247	M	1
Cm-248	M	1
Cm-249	M	1
Cm-250	M	1
Bk-247	M	1
Bk-248m	M	1
Bk-249	M	1
Bk-250	M	1
Cf-249	M	1
Cf-250	M	1
Cf-251	M	1
Cf-252	*M*	1
Es-253	M	1
Es-254	M	1

Shaded cell = new nuclide or updated absorption type in CAP88-PC V4.1.1 or a newly reported in PNNL-PTE-rev5.. Absorption type B = blank, no internal dose factors available for this (parent) nuclide with a default particle size of 0 micrometers.

(a) *V* = vapor; E = elemental; O = organic compounds; F = particulate, fast clearance rate; M = particulate, moderate clearance rate; S = particulate, slow clearance rate. Carbon isotopes are modeled as particulate (M), carbon monoxide (CO), or carbon dioxide (CO2). DCFPAK3.02 (Eckerman and Leggett. 2013)

(b) Particulates listed with a particle size of 0 reflect the only available option in CAP88-PC V4.1.1.

(c) Radionuclide not available in CAP88-PC V4.1.1.

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