PNNL-22342-7

Pacific Northwest
NATIONAL LABORATORY

Department of Energy – Office of Science
Pacific Northwest National Laboratory

# Marine Sciences Laboratory Radionuclide Air Emissions Report for Calendar Year 2018

SF Snyder
JM Barnett

May 2019

U.S. DEPARTMENT OF
ENERGY

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Prepared for
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Pacific Northwest National Laboratory
Richland, Washington 99352

# Summary

The U.S. Department of Energy Office of Science Pacific Northwest Site Office has oversight and stewardship duties associated with the Pacific Northwest National Laboratory Marine Sciences Laboratory (MSL), located on Battelle Land-Sequim. Facility operations include radiological operations with the potential to emit low levels of radioactive materials.

This report is prepared to document compliance with the Code of Federal Regulations, Title 40, Protection of the Environment, Part 61, *National Emission Standards for Hazardous Air Pollutants*, Subpart H, "National Emission Standards for Emissions of Radionuclides Other than Radon from Department of Energy Facilities" and Washington Administrative Code Chapter 246-247, *Radiation Protection–Air Emissions*. Compliance is determined by comparing the estimated effective dose equivalent (EDE) to the maximally exposed individual (MEI) with the 10 millirem per year (mrem/yr) U.S. Environmental Protection Agency (EPA) standard. The MSL has only fugitive emissions sources. Despite the fact that the regulations are intended for application to point source emissions, fugitive emissions are included with regard to complying with the EPA standard.

The EDE to the MSL MEI due to routine operations in 2018 was 4.5E-04 mrem (4.5E-6 mSv). No non-routine emissions occurred in 2018. The MSL is in compliance with the federal and state 10 mrem/yr standard.

For further information concerning this report, you may contact Thomas M. McDermott, U.S. Department of Energy, Pacific Northwest Site Office, by telephone at (509) 372 4675 or by e-mail at tom.mcdermott@science.doe.gov.

## CERTIFICATION OF PNNL-22342-7

# DOE-SC
# Pacific Northwest National Laboratory
# Marine Sciences Laboratory
# Radionuclide Air Emissions Report
# Calendar Year 2018

I certify under penalty of law that I have personally examined and am familiar with the information submitted herein and, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment. See, 18 U.S.C. 1001. [verbatim from 40 CFR 61, Subpart H, 61.94(b)(9)]

Roger E. Snyder, Manager
U.S. Department of Energy
Pacific Northwest Site Office

5/20/19
Date

# Acronyms and Abbreviations

| | |
|---|---|
| CFR | Code of Federal Regulations |
| Ci | curie |
| CY | calendar year |
| DOE | U.S. Department of Energy |
| DOE-SC | U.S. Department of Energy, Office of Science |
| EDE | effective dose equivalent |
| EPA | U.S. Environmental Protection Agency |
| Major | a radioactive point source having a radiological dose potential of greater than 0.1 mrem/yr EDE, based on emissions that would result if all pollution-control equipment did not exist but facility operations were otherwise normal |
| MEI | maximally exposed individual |
| Minor | a radioactive point source having a radiological dose potential of less than or equal to 0.1 mrem/yr EDE, based on emissions that would result if all pollution-control equipment did not exist but facility operations were otherwise normal |
| mrem | millirem [i.e., $1 \times 10^{-3}$ rem] |
| MSL | Pacific Northwest National Laboratory Marine Sciences Laboratory |
| mSv | millisievert |
| NESHAP | National Emission Standards for Hazardous Air Pollutants |
| NOC | Notice of Construction |
| PNNL | Pacific Northwest National Laboratory |
| PTE | potential-to-emit |
| RAEL | Radioactive Air Emissions License |
| rem | roentgen equivalent man |
| UDF | unit-release dose factor |
| WAC | Washington Administrative Code |
| WDOH | Washington State Department of Health |

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# 1.0 Introduction

The Pacific Northwest National Laboratory (PNNL) Marine Sciences Laboratory (MSL) is located on Battelle Land-Sequim (PNSO 2017) on the coast of Washington State's Olympic Peninsula (Figure 1.1). The Pacific Northwest Site Office of the U.S. Department of Energy (DOE) Office of Science oversees MSL activities through an exclusive use contract with Battelle Memorial Institute. MSL is DOE's only marine research laboratory.

This radiological air emissions report meets the Washington Department of Health (WDOH) requirements for radiological National Emission Standards for Hazardous Air Pollutants (NESHAP) compliance reporting for the activities at MSL for calendar year (CY) 2018. The WDOH Radioactive Air Emissions License (RAEL)-014, Renewal 1, was issued in January 2018. This renewal changed the release to a single, fugitive site-wide emission unit. Compared to the prior year, radiological laboratory activities have not changed under the new license.

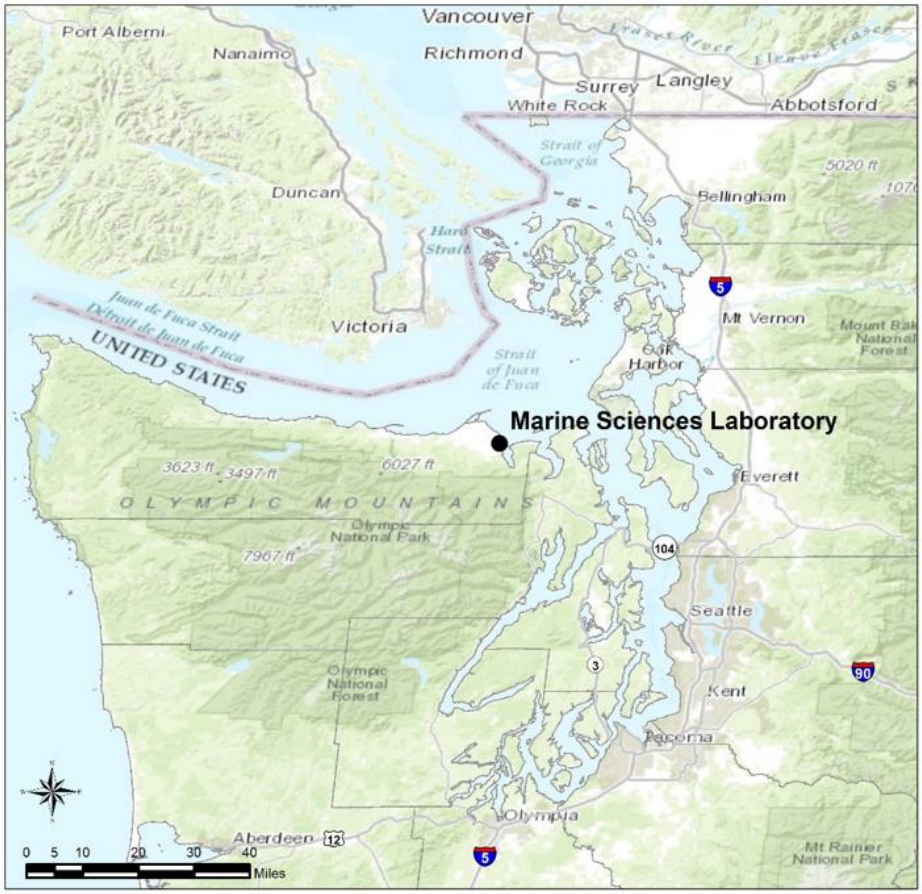


**Figure 1.1**. MSL in Northwestern Washington State

## 1.1 Battelle Land-Sequim and MSL Description

Battelle Land-Sequim (Figure 1.2) encompasses 150 acres of uplands and tidelands, of which about 7.5 acres has been developed for research operations. The research operations occur at several laboratories and other facilities in an area referred to as MSL, which includes analytical and general purpose laboratories and wet or support laboratories supplied with heated and cooled freshwater and seawater. MSL has two buildings with the potential to emit low levels of radioactive material. In addition, MSL has a state-of-the-art waste seawater treatment system, a dock facility for a 28-foot research vessel, and a specialized scientific diving boat.

Battelle Land-Sequim lies on the shores of the Strait of Juan de Fuca and is in the rain shadow of the Olympic Mountains in Clallam County, at approximate coordinates 48°04’40” N, 123°02’55” W. Despite its coastal location, it receives less than 15 inches of rainfall on average annually. Average monthly temperatures range from 31°F to 70°F. Meteorology at the Sequim Site in 2018 is summarized in Table 1.1. Wind speeds were below average in 2018.

Nearby cities are Sequim (population 6,600), Port Angeles (population 19,000), and Port Townsend (population 9,100) (DOC 2011). Seattle is approximately 50 miles from MSL. The nearest sea border with Canada is about 17 miles from MSL in the Salish Sea; the nearest Canadian land border is about 25 miles northwest from MSL.

Radiological emissions predominantly occur from laboratories in two buildings: MSL-1 and MSL-5 (Figure 1.2, Figure 1.3, and Figure 1.4). Radiological laboratories activities at MSL include:

- conducting biological, chemical, and physical studies in which marine or aquatic environmental conditions need to be maintained;
- maintenance of a “cleanroom” for ultra-low-level trace measurements in environmental media;
- storage of radioactive and mixed waste; and
- laboratory space that could be set up for radiological work.

**Figure 1.2.** Battelle Land-Sequim and Marine Sciences Laboratory

**Table 1.1**. 2018 Meteorological Summary for Sequim, Washington

| Parameter | 2018 value |
|---|---|
| Average Temperature | 50.4°F (10.2°C) |
| Average Wind Speed | 2.9 mph (1.3 m/s) |
| Predominant Wind Direction (from) | W |
| Total Precipitation | 14.86 in. (37.7 cm) |

Data courtesy of WSU AgWeatherNet (accessed 3/13/19: http://weather.wsu.edu/?p=93250 / Sequim Station).

**Figure 1.3**. MSL-1 Building

**Figure 1.4**. MSL-5 Building

# 2.0 Radionuclide Air Emissions

This section describes the registered MSL emission unit and presents emissions estimates for operations during CY 2018.

## 2.1 Major, Minor, and Fugitive Emissions Points

A single nonpoint source minor emission unit, J-MSL, is registered with the state of Washington under the RAEL-014, Renewal-1. Radioactive air emissions continue to be well below the criteria for classification as a minor emission unit (i.e., potential-to-emit [PTE] contribution is < 0.1 millirem per year [mrem/yr] effective dose equivalent [EDE] to the maximally exposed individual [MEI]). Information regarding the radionuclides of concern, emission rates, and emission unit physical characteristics are described below. J-MSL is also classified as a PIC-4 (licensed PTE of ≤ 0.001 mrem/yr) emission unit (Barnett 2018).

J-MSL is a sitewide emission unit. Essentially, any structure or abatement controls from which an emission traverses is disregarded when compliance determinations are estimated.

Radiological operations at MSL emit very low levels of radioactive materials. Appendix A contains the full list of radionuclides that may be handled at MSL. The 2018 radioactive material emissions to the air are given in Table 2.1. The 40 CFR 61, Appendix D method of determining unabated emissions was used. Beta emissions include a significant I-125 component (1.00E-6 Ci) with all other beta-emitter activity emissions of 2.07E-9 Ci.

**Table 2.1**. 2018 MSL Emissions Estimates

| Nuclide / Type | | 2018 – J-MSL[a,b] (Ci) |
|---|---|---|
| H-3 | Beta | 6.95E-11 |
| C-14 | Beta | 2.48E-13 |
| K-40 | Beta | 7.65E-12 |
| Fe-55 | Beta | 3.46E-14 |
| Co-57 | Beta | 1.31E-09 |
| Co-60 | Beta | 1.23E-13 |
| Sr-90 | Beta | 1.56E-12 |
| Tc-99 | Beta | 3.00E-10 |
| Ru-106 | Beta | 7.83E-13 |
| Sb-125 | Beta | 1.06E-12 |
| I-125 | Beta | 1.00E-06 |
| I-129 | Beta | 2.43E-15 |
| Cs-134 | Beta | 6.28E-12 |
| Cs-137 | Beta | 1.86E-10 |
| Ba-133 | Beta | 1.84E-10 |
| Eu-152 | Beta | 6.19E-14 |
| Eu-154 | Beta | 1.50E-13 |
| Eu-155 | Beta | 1.77E-14 |
| Pb-210 | Beta | 1.28E-13 |
| Po-208 | Alpha | 6.96E-10 |
| Po-209 | Alpha | 1.40E-11 |
| Ra-226 | Alpha | 4.33E-13 |
| Ra-228 | Beta | 4.96E-14 |
| Th-228 | Alpha | 2.60E-13 |
| Th-230 | Alpha | 1.53E-13 |
| Th-232 | Alpha | 1.00E-09 |
| U-233 | Alpha | 6.70E-15 |
| U-234 | Alpha | 7.76E-09 |
| U-235 | Alpha | 3.59E-10 |
| U-238 | Alpha | 8.59E-09 |
| Pu-238 | Alpha | 8.18E-14 |
| Pu-239 | Alpha | 3.75E-13 |
| Pu-240 | Alpha | 3.75E-13 |
| Pu-241 | Beta | 4.66E-14 |
| Am-241 | Alpha | 4.34E-13 |
| | **Total Alpha Ci** | 1.84E-08 |
| | **Total Beta Ci** | 1.00E-06 |
| | **TOTAL (Ci)** | **1.02E-06** |

(a) "Beta" (gray-shaded) includes beta- and gamma-emitters.
(b) Emissions based on 40 CFR 61, Appendix D methods.

# 3.0 Dose Assessment

This section describes the potential impact of MSL radiological air emissions. Radiological operations at MSL have not changed from the prior year. The license has changed from the prior year, resulting in a change to dose assessment methods. A review of radiological assessment needs under the license renewal is nearing completion, as an update to the Data Quality Objects report (Barnett et al. 2012).

## 3.1 Dose Model and Potential Receptors

The COMPLY Code version 1.7 (Level 4) (EPA 1989) was used for estimating dose for comparison to the U.S. Environmental Protection Agency (EPA) standard of 10 mrem/yr EDE to any member of the public (40 CFR 61, Subpart H, and WAC 246-247). This code is approved for use for compliance determination (40 CFR 61, Subpart H). Some input parameters were changed in consideration of the license renewal (Table 3.1), including release parameters, wind speed, and distance to receptor.

The release height and building dimensions were both reduced from 8 m and 8 m × 30 m, respectively, to 5 m and 5 m × 5 m. Also, the distance from source-to-receptor was updated to reflect the use of a "Central MSL" emission location assumption (48° 4' 42.45", 123° 2' 48.51"; Google Earth, image date July 30, 2017) (see Figure 1.2, yellow marker). This Central MSL location was selected because it is considered central to all operations areas at MSL. Distances from the Central MSL upland assumed release location to lowland boundary locations consider the straight-line rather than horizontal (map) distance; this accounts for the additional plume transport distance resulting from vertical difference of the upland (~30 m above the shore) and shore boundaries.

**Table 3.1**. COMPLY Input Parameters

| Parameter | J-MSL Value (Level 4) |
|---|---|
| Nuclide names | <varies by year> |
| Concentrations (Ci/m$^3$) | NA |
| Annual possession amount (Ci) | NA |
| Release rates (Ci/yr *or* Ci/s) | <varies by year> |
| Release height (m) | 5 m |
| Building height (m) | 5 m |
| Stack or vent diameter (m) | NA |
| Volumetric flow rate (m$^3$/s) | NA |
| Distance from source-to-receptor (m) | 234 m[(a)] |
| Building width (m) | 5 m |
| Wind speed (m/s) | 1.3 m/s |
| Distances to sources of food production (m) | 234 m[(a)] |
| Stack temperature (°F) | NA |
| Ambient air temperature (°F) | NA |
| Wind rose | NA(nwr)[(b)] |
| Building length | NA(nwr)[(b)] |

NA = not applicable.
(a) Smallest potential MEI distance.
(b) NA(nwr) = not applicable because **n**o **w**ind **r**ose data is used.

Potential MEI locations for each of the 16 compass directions are provided in Table 3.2. The nearest location where a member of the public would actually reside or abide (e.g., dwelling, business, school, office) relative to the Central MSL emission location was determined to be 234 m W and is designated as the MEI location (40 CFR Part 61, Subpart H, and WAC 2019) because no wind rose is entered in the COMPLY modeling.

Potential maximum annual air locations are boundary locations in each of the 16 compass directions provided in Table 3.2. The maximum annual air location (WAC 2007) dose was calculated for the nearest boundary location, 129 m ENE of the Central MSL. No members of the public routinely inhabit this shore, boundary location; food modeling in COMPLY for this location assumed food to be grown at a distance resulting from averaging all terrestrial boundary distances, 355 m from Central MSL, as an overestimating assumption.

**Table 3.2**. Potential MSL MEI Locations and Distances to Boundary

| Direction from Central MSL | Smallest Distance to a Potential MEI Location | Smallest Distance to the Battelle Land-Sequim Boundary |
|---|---|---|
| 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 | 715 m |
| SSW | 723 m, res | 753 m |
| SW | 340 m, res | 270 m |
| WSW | 276 m, res | 203 m |
| W | 234 m, res | 187 m |
| WNW | 440 m, res | 202 m |
| NW | 1,261 m, busi | 290 m |
| NNW | 840 m, res | 220 m |

Central MSL point and Battelle Land-Sequim (see Figure 1.2).
Blue cell highlight = a shoreline location where no member of the public could occupy 24/7.
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).

## 3.2 Compliance Assessment

The dose standard in 40 CFR 61, Subpart H, applies to radionuclide air emissions, other than radon, from DOE facilities. The emissions from Table 2.1 resulted in the MEI doses reported in Table 3.3.

Doses were estimated using a unit-release dose factor ($UDF_r$) times the release rate ($A_r$) for radionuclide "r" [i.e., $UDF_r$ (mrem/yr per 1 $Ci_{released}$/yr) × $A_r$ ($Ci_{releasead}$) = $D_r$ (mrem/yr)]. COMPLY v1.7.1-determined UDFs used in the 2018 dose assessment are indicated in Appendix B.

As a conservative (overestimating) assumption, all alpha activity releases except for Th-232 were assumed to be Am-241. The Th-232 dose was estimated separately because the generic alpha-emitter

(Am-241) assumption does not produce a conservative dose result. All beta activity releases except for I-125 were assumed to be Cs-137. The I-125 dose was estimated separately because the generic beta-emitter (Cs-137) assumption overestimates this nuclide dose excessively and would result in a total dose over the RAEL-014 emission unit limit. For other nuclides where the generic nuclide does not produce a conservative result (i.e., I-129, Pb-210, and Ra-228), external calculations were done to make sure a nuclide-specific dose calculation is not a significant portion of the final reported dose (I-129 = 4E-12 mrem/yr; Pb-210 = 1.9E-10 mrem/yr; and Ra-228 = 3.9E-11 mrem/yr).

For CY 2018, the dose assigned to the MSL MEI overestimates any actual offsite dose. The MEI dose was calculated for the nearest potential receptor, 234 m (768 ft) W of Central MSL.

**Table 3.3**. MSL 2018 MEI Dose

| Data/Emission Type | J-MSL |
|---|---|
| **Releases** | |
| Th-232 (Ci) | 1.00E-09 |
| I-125 (Ci) | 1.00E-06 |
| Remaining Alpha (Ci) | 1.74E-08 |
| Remaining Beta (Ci) | 2.07E-09 |
| **Total** | **1.02E-06 Ci** |
| **Annual MEI Dose** | |
| Th-232 (mrem) | 5.87E-05 |
| I-125 (mrem) | 1.13E-04 |
| Remaining Alpha (mrem) [(a)] | 2.73E-04 |
| Remaining Beta (mrem) [(b)] | 1.30E-06 |
| **Total** | **4.46E-04 mrem** |
| **Dose Contribution** | |
| Alpha | 74% |
| Beta | 26% |

(a) Unit dose factor for Am-241 applied to estimated dose.
(b) Unit dose factor for Cs-137 applied to estimate dose.

The EDE to the 2018 MSL MEI from routine J-MSL emissions was 4.5E-04 mrem (4.5E-06 mSv) for 40 CFR Part 61, Subpart H, and WAC 246-247 compliance reporting. Table 3.3 shows the relative contributions of each nuclide and facility to the MEI dose. The 2017 MEI estimate was 1.6E-4 mrem/yr (1.6E-06 mSv/yr) EDE (also see Snyder and Barnett 2018).

Comparing the MSL 2018 MEI dose to average U.S. background radiation (NCRP 2009):

| | | |
|---|---|---|
| • Annual natural background radiation | 310.0 | mrem/yr |
| • Daily natural background radiation | 0.85 | mrem/d |
| • Hourly natural background radiation | 0.035 | mrem/hr |
| • Per minute natural background radiation | 0.00059 | mrem/min |
| • **MSL 2018 MEI dose** | **0.00045** | **mrem/yr** |
| • Per second natural background radiation | 0.0000098 | mrem/sec |

The EDE to the boundary location where air concentrations of radioactive materials are modeled to be greatest is the nearest distance to the site boundary (see Table 3.2). This location, 129 m (423 ft) ENE of the Central MSL location, is on the shore. Food (vegetables, milk, meat) was assumed to be grown 355 m from the release location. The estimated dose to this individual assumed to be at this shore location 24/7 is 1.0E-03 mrem (1.0E-05 mSv), which is well below the 10 mrem/yr dose standard for WAC 2007 reporting.

# 4.0 Supplemental Information

This section provides supplemental information related to MSL radionuclide air emissions in 2018. Supplemental information is provided as part of a Memorandum of Understanding between DOE and EPA (DOE 1995). Collective dose information is reported under DOE O 458.1 requirements (DOE 2011).

## 4.1 Collective Dose Estimate

An estimated 2.35 million people live within 50 miles (80 km) of MSL, with about 362,000 of those residing in Canada (Zuljevic et al. 2016). The populations and the major U.S. cities at various distances from MSL are given in Table 4.1. Victoria, British Columbia, is the only major Canadian city within 50 miles of MSL and is more than 20 miles from MSL.

**Table 4.1**. Populations and Significant U.S. Cities within 50 miles of MSL

| Population at Indicated Distance[(a)] | Distance (miles) | Cities at Indicated Distances |
|---|---|---|
| 29,097 | 0–10 | City of Sequim |
| 55,533 | 10–20 | Port Angeles |
| 240,311 | 20–30 | Oak Harbor |
| 701,151 | 30–40 | Anacortes, Bremerton (portion), Edmonds, Everett (portion), Friday Harbor, Marysville (portion), Poulsbo, Shoreline, Stanwood |
| 1,322,999 | 40–50 | Bothell, Bremerton (portion), Everett (portion), Kirkland, Lynnwood, Marysville (portion), Mount Vernon, Seattle (large portion), West Seattle |

(a) Zuljevic et al. 2016

The 2018 collective dose was estimated assuming that the total curies released (Table 3.3) were dispersed in a single direction. The maximum collective dose was determined to result from dispersion to the west, which only contains U.S. populations. The MEI dose (4.5E-4 mrem) was multiplied by a population-weighted air concentration in the direction of maximum collective impact for a collective dose of 5.0E-4 person-rem. If the release were dispersed only to the maximum Canadian sector (NNW), the maximum estimated Canadian collective dose would be 2.0E-4 person-rem. Dispersal toward the large, but distant, Seattle population sector (SE) would have resulted in a collective dose about 75% less than the collective U.S. dose indicated.

## 4.2 Compliance Status with Subparts Q and T of 40 CFR 61

- No storage or disposal of radium-bearing materials occurs at MSL; therefore, 40 CFR 61, Subpart Q does not apply to MSL operations.
- No uranium mill tailings or ore disposal activities have been conducted at MSL; therefore, 40 CFR 61, Subpart T does not apply to MSL operations.

## 4.3 Other Supplemental Information

- Periodic confirmatory measurement information is not required by the Notices of Construction (NOCs).
- The PNNL Radioactive Material Tracking system is used to manage potential emissions below permit thresholds, resulting in overall confirmation of inventory limits and emissions estimates to respective NOCs.
- Quality assurance program status of compliance with 40 CFR 61, Appendix B, Method 114 does not apply because no air sampling is conducted at MSL.
- There were no radon emissions in 2018.
- There were no unplanned emissions in 2018.

# 5.0 References


40 CFR 61, as amended. *National Emission Standards for Hazardous Air Pollutants* (NESHAP), Appendix B, "Test Methods."

40 CFR 61, as amended. *National Emission Standards for Hazardous Air Pollutants* (NESHAP), Appendix D, "Methods for Estimating Radionuclide Emissions."

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# Appendix A

# List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2018

# Appendix A: List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2018

**Table A.1.** List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2018

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ac-225 | Au-195 | C-11 | Co-58m | F-18 | Ho-166 | K-42 | Nb-91 | Pa-234m |
| Ac-226 | Au-195m | C-14 | Co-60 | Fe-55 | Ho-166m | Kr-81 | Nb-91m | Pb-203 |
| Ac-227 | Au-196 | C-15 | Co-60m | Fe-59 | I-122 | Kr-81m | Nb-92 | Pb-204m |
| Ac-228 | Au-196m | Ca-41 | Cr-49 | Fr-221 | I-123 | Kr-83m | Nb-92m | Pb-205 |
| Ag-105 | Au-198 | Ca-45 | Cr-51 | Fr-222 | I-124 | Kr-85 | Nb-93m | Pb-209 |
| Ag-106m | Au-198m | Ca-47 | Cr-55 | Fr-223 | I-125 | Kr-85m | Nb-94 | Pb-210 |
| Ag-108 | Au-199 | Cd-107 | Cs-131 | Ga-67 | I-126 | Kr-87 | Nb-94m | Pb-211 |
| Ag-108m | Ba-131 | Cd-109 | Cs-132 | Ga-68 | I-128 | Kr-88 | Nb-95 | Pb-212 |
| Ag-109m | Ba-131m | Cd-111m | Cs-134 | Ga-70 | I-129 | Kr-89 | Nb-95m | Pb-214 |
| Ag-110 | Ba-133 | Cd-113 | Cs-134m | Ga-72 | I-130 | Kr-90 | Nb-96 | Pd-103 |
| Ag-110m | Ba-133m | Cd-113m | Cs-135 | Gd-148 | I-130m | La-137 | Nb-97 | Pd-107 |
| Ag-111 | Ba-135m | Cd-115 | Cs-135m | Gd-149 | I-131 | La-138 | Nb-97m | Pd-109 |
| Ag-111m | Ba-137m | Cd-115m | Cs-136 | Gd-150 | I-132 | La-140 | Nb-98 | Pd-109m |
| Ag-112 | Ba-139 | Cd-117 | Cs-137 | Gd-151 | I-132m | La-141 | Nd-144 | Pd-111 |
| Al-26 | Ba-140 | Cd-117m | Cs-138 | Gd-152 | I-133 | La-142 | Nd-147 | Pd-112 |
| Al-28 | Ba-141 | Ce-139 | Cs-138m | Gd-153 | I-133m | La-144 | Ni-56 | Pm-143 |
| Am-240 | Ba-142 | Ce-141 | Cs-139 | Gd-159 | I-134 | Lu-177 | Ni-57 | Pm-144 |
| Am-241 | Ba-143 | Ce-142 | Cs-140 | Ge-68 | I-134m | Lu-177m | Ni-59 | Pm-145 |
| Am-242 | Be-10 | Ce-143 | Cs-141 | Ge-69 | I-135 | Mg-27 | Ni-63 | Pm-146 |
| Am-242m | Be-7 | Ce-144 | Cu-64 | Ge-71 | In-106 | Mg-28 | Ni-65 | Pm-147 |
| Am-243 | Bi-207 | Cf-249 | Cu-66 | Ge-71m | In-111 | Mn-52 | Np-235 | Pm-148 |
| Am-244 | Bi-208 | Cf-250 | Cu-67 | Ge-75 | In-111m | Mn-52m | Np-236 | Pm-148m |
| Am-244m | Bi-210 | Cf-251 | Dy-159 | Ge-77 | In-112 | Mn-53 | Np-236m | Pm-149 |
| Am-245 | Bi-210m | Cf-252 | Dy-165 | Ge-77m | In-112m | Mn-54 | Np-237 | Pm-150 |
| Am-246 | Bi-211 | Cl-36 | Dy-169 | H-3 | In-113m | Mn-56 | Np-238 | Pm-151 |
| Ar-37 | Bi-212 | Cm-241 | Er-169 | Hf-175 | In-114 | Mo-93 | Np-239 | Po-208 |
| Ar-39 | Bi-213 | Cm-242 | Er-171 | Hf-177m | In-114m | Mo-93m | Np-240 | Po-209 |
| Ar-41 | Bi-214 | Cm-243 | Es-254 | Hf-178m | In-115 | Mo-99 | Np-240m | Po-210 |
| Ar-42 | Bk-247 | Cm-244 | Eu-150 | Hf-179m | In-115m | Mo-103 | O-15 | Po-211 |
| As-73 | Bk-248m | Cm-245 | Eu-150m | Hf-180m | In-116 | Mo-104 | O-19 | Po-212 |
| As-74 | Bk-249 | Cm-246 | Eu-152 | Hf-181 | In-116m | Mo-105 | Os-185 | Po-212m |
| As-76 | Bk-250 | Cm-247 | Eu-152m | Hf-182 | In-117 | N-13 | Os-191 | Po-213 |
| As-77 | Br-82 | Cm-248 | Eu-152n | Hg-203 | In-117m | Na-22 | P-32 | Po-214 |
| At-217 | Br-82m | Cm-249 | Eu-154 | Hg-205 | Ir-189 | Na-24 | P-33 | Po-215 |
| At-218 | Br-83 | Cm-250 | Eu-154m | Hg-206 | Ir-190 | Na-24m | Pa-231 | Po-216 |
| Au-193 | Br-84 | Co-56 | Eu-155 | Ho-163 | Ir-192 | Nb-100 | Pa-232 | Po-218 |
| Au-193m | Br-84m | Co-57 | Eu-156 | Ho-164 | Ir-194 | Nb-101 | Pa-233 | Pr-142 |

Table A.1 (cont'd)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pr-143 | Ra-226 | Rh-104m | Sc-44m | Sn-125 | Tc-98 | Th-233 | U-240 | Y-91m |
| Pr-144 | Ra-227 | Rh-105 | Sc-46 | Sn-125m | Tc-99 | Th-234 | V-48 | Y-92 |
| Pr-144m | Ra-228 | Rh-105m | Sc-47 | Sn-126 | Tc-99m | Ti-44 | V-49 | Y-93 |
| Pt-191 | Rb-81 | Rh-106 | Sc-48 | Sr-82 | Tc-101 | Ti-45 | W-181 | Yb-164 |
| Pt-193 | Rb-81m | Rn-218 | Se-75 | Sr-83 | Tc-103 | Ti-51 | W-185 | Yb-165 |
| Pt-193m | Rb-82 | Rn-219 | Se-77m | Sr-85 | Tc-106 | Tl-200 | W-185m | Yb-166 |
| Pt-195m | Rb-82m | Rn-220 | Se-79 | Sr-85m | Te-121 | Tl-201 | W-187 | Yb-167 |
| Pt-197 | Rb-83 | Rn-222 | Se-79m | Sr-87m | Te-121m | Tl-202 | W-188 | Yb-169 |
| Pt-197m | Rb-84 | Rn-224 | Si-31 | Sr-89 | Te-123 | Tl-204 | Xe-122 | Yb-175 |
| Pt-198m | Rb-84m | Ru-103 | Si-32 | Sr-90 | Te-123m | Tl-206 | Xe-123 | Yb-177 |
| Pt-199 | Rb-86 | Ru-105 | Sm-145 | Sr-91 | Te-125m | Tl-206m | Xe-125 | Zn-65 |
| Pt-199m | Rb-86m | Ru-106 | Sm-146 | Sr-92 | Te-127 | Tl-207 | Xe-127 | Zn-69 |
| Pu-234 | Rb-87 | Ru-97 | Sm-147 | Ta-179 | Te-127m | Tl-208 | Xe-127m | Zn-69m |
| Pu-235 | Rb-88 | S-35 | Sm-148 | Ta-180 | Te-129 | Tl-209 | Xe-129m | Zr-88 |
| Pu-236 | Rb-89 | Sb-122 | Sm-151 | Ta-182 | Te-129m | Tl-210 | Xe-131m | Zr-89 |
| Pu-237 | Rb-90 | Sb-122m | Sm-153 | Ta-182m | Te-131 | Tm-168 | Xe-133 | Zr-89m |
| Pu-238 | Rb-90m | Sb-124 | Sm-155 | Ta-183 | Te-131m | Tm-170 | Xe-133m | Zr-93 |
| Pu-239 | Re-186 | Sb-124m | Sm-156 | Tb-157 | Te-132 | Tm-171 | Xe-135 | Zr-95 |
| Pu-240 | Re-186m | Sb-124n | Sm-157 | Tb-158 | Te-133 | U-232 | Xe-135m | Zr-97 |
| Pu-241 | Re-187 | Sb-125 | Sn-113 | Tb-160 | Te-133m | U-233 | Xe-137 | Zr-98 |
| Pu-242 | Re-188 | Sb-126 | Sn-113m | Tb-161 | Te-134 | U-234 | Xe-138 | Zr-99 |
| Pu-243 | Rh-101 | Sb-126m | Sn-117m | Tc-95 | Th-227 | U-235 | Xe-139 | Zr-100 |
| Pu-244 | Rh-101m | Sb-127 | Sn-119m | Tc-95m | Th-228 | U-235m | Y-88 | - |
| Pu-246 | Rh-102 | Sb-128 | Sn-121 | Tc-96 | Th-229 | U-236 | Y-89m | - |
| Ra-223 | Rh-102m | Sb-128m | Sn-121m | Tc-96m | Th-230 | U-237 | Y-90 | - |
| Ra-224 | Rh-103m | Sb-129 | Sn-123 | Tc-97 | Th-231 | U-238 | Y-90m | - |
| Ra-225 | Rh-104 | Sc-44 | Sn-123m | Tc-97m | Th-232 | U-239 | Y-91 | - |

# Appendix B

# COMPLY Unit Dose Factors

# Appendix B: COMPLY Unit Dose Factors

COMPLY v1.7.1 (EPA 1989) was used to determine unit-release dose factors, which represent impacts to a hypothetical receptor 234 m from the *Central MSL* point of assumed releases. No wind rose was supplied, meaning the default assumption of wind blowing toward the receptor 25% of the time was used. COMPLY Level 4 with no wind rose was used; other assumptions are listed in Table 3.1 of the main report, including an annual average wind speed (2018) of 1.3 m/s.

The appropriate solubility class (DOE 2010) was applied, replacing the DOE 2010 solubility classifications (F,M,S) with the analogous solubility classifications available in COMPLY (D,W,Y, respectively). The COMPLY default inhalation solubility class, in the following table, are used as simplifying, overestimating assumptions for dose determination (see solubility class preferences in Table 3.1 of Snyder and Rokkan 2016).

**Table B.1**. MSL Unit Dose Factors

| Nuclide | Footnote | COMPLY Solubility Class | Unit Dose Factor (mrem/yr EDE per Ci/yr released) |
|---|---|---|---|
| **Am-241** | | W | 15700 |
| Cs-137 | | D | 627 |
| I-125 | | D | 113 |
| I-129 | | D | 1680 |
| Pb-210 | a | D | 1470 |
| Ra-228 | | W | 792 |
| **Th-232** | b | W | 58700 |

**Bold font** = alpha-emitting nuclides. All others are beta/gamma emitters.
(a) The solubility class listed is the only available option in COMPLY v1.7.1.
(b) Solubility class S is preferred, but the default class W used as an overestimating assumption.

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