PNNL-22342-4

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**Pacific Northwest National Laboratory**

# Marine Sciences Laboratory Radionuclide Air Emissions Report for Calendar Year 2015

SF Snyder
JM Barnett

May 2016

U.S. DEPARTMENT OF ENERGY

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

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Pacific Northwest National Laboratory
Richland, Washington 99352

# Summary

The U.S. Department of Energy Office of Science (DOE-SC) 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. The facility has two buildings with the potential to emit low levels of radioactive materials. DOE-SC contracted for exclusive use of its radiological operations effective October 1, 2012.

This report is prepared to document compliance with the Code of Federal Regulation, 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 indicated 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.

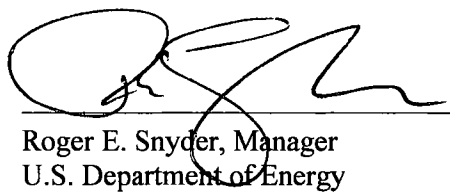
The EDE to the MSL MEI due to routine operations in 2015 was 1.1E-04 mrem (1.1E-06 mSv). No non-routine emissions occurred in 2015. The MSL is in compliance with the federal and state 10 mrem/yr standard.

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-22342-4

# DOE-SC
# Pacific Northwest National Laboratory
# Marine Sciences Laboratory
# Radionuclide Air Emissions Report
# Calendar Year 2015

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)]



6/10/16

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

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 |
| HEPA | high efficiency particulate air (filter) |
| 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 |
| PNSO | Pacific Northwest Site Office |
| PTE | potential-to-emit |
| QA | quality assurance |
| 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 2013) 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) 2015.

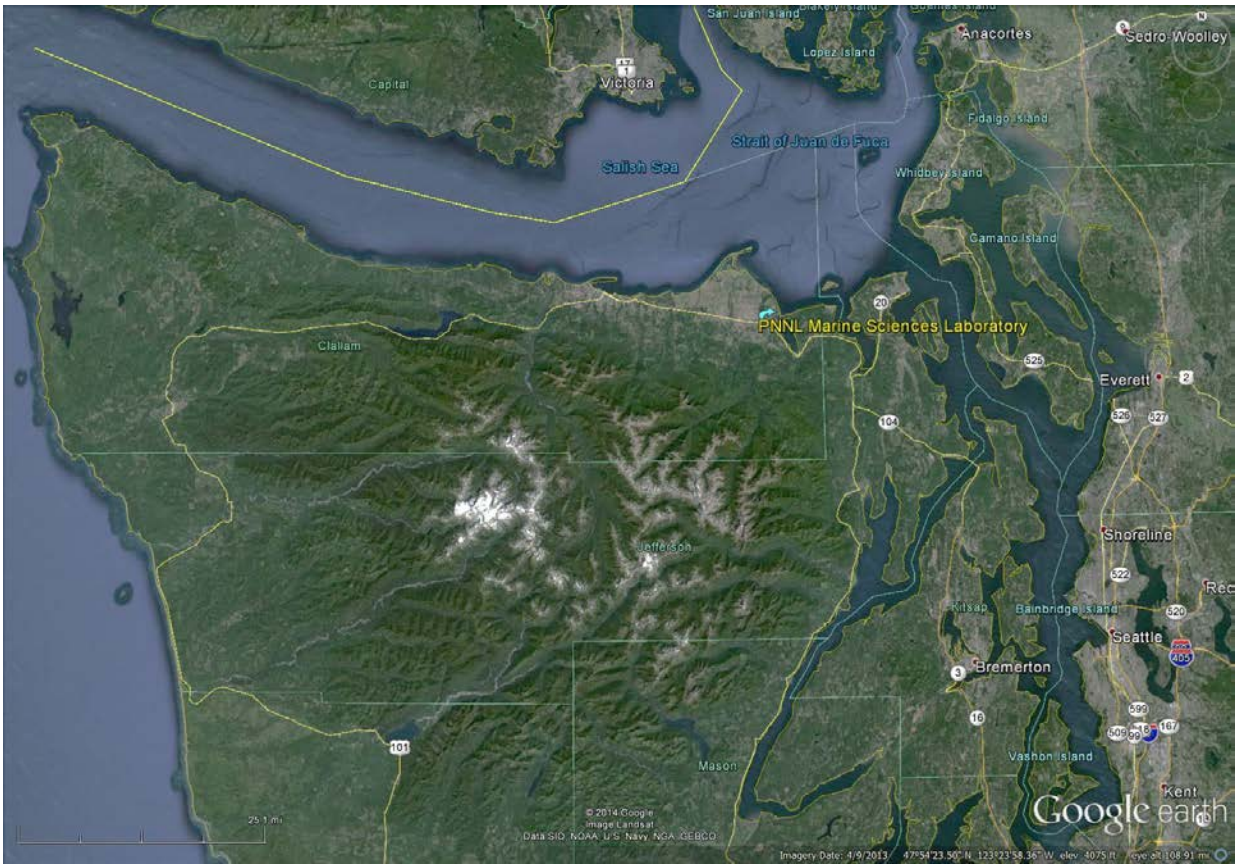


**Figure 1.1**. MSL in Northwestern Washington State

## 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 emission units 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. 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 (mi) from MSL. The nearest sea border with Canada is about 17 mi from MSL in the Salish Sea; the nearest Canadian land border is about 25 mi northwest from MSL.

Emission points are located in buildings MSL-1 and MSL-5. The MSL-1 Building (Figure 1.3) contains facilities for biological, chemical, and physical studies in which marine or aquatic environmental conditions need to be maintained. This facility also houses a “cleanroom” for ultra-low-level trace measurements in environmental media, an electronics shop, and diving equipment storage. The MSL-5 Building (Figure 1.4) contains all-purpose chemistry and biochemistry laboratories. One laboratory in MSL-5 is set up for work with radionuclides; however, any laboratory could be set up for such work. A location for storage of hazardous, radioactive, and mixed waste is provided in MSL-5 Building.

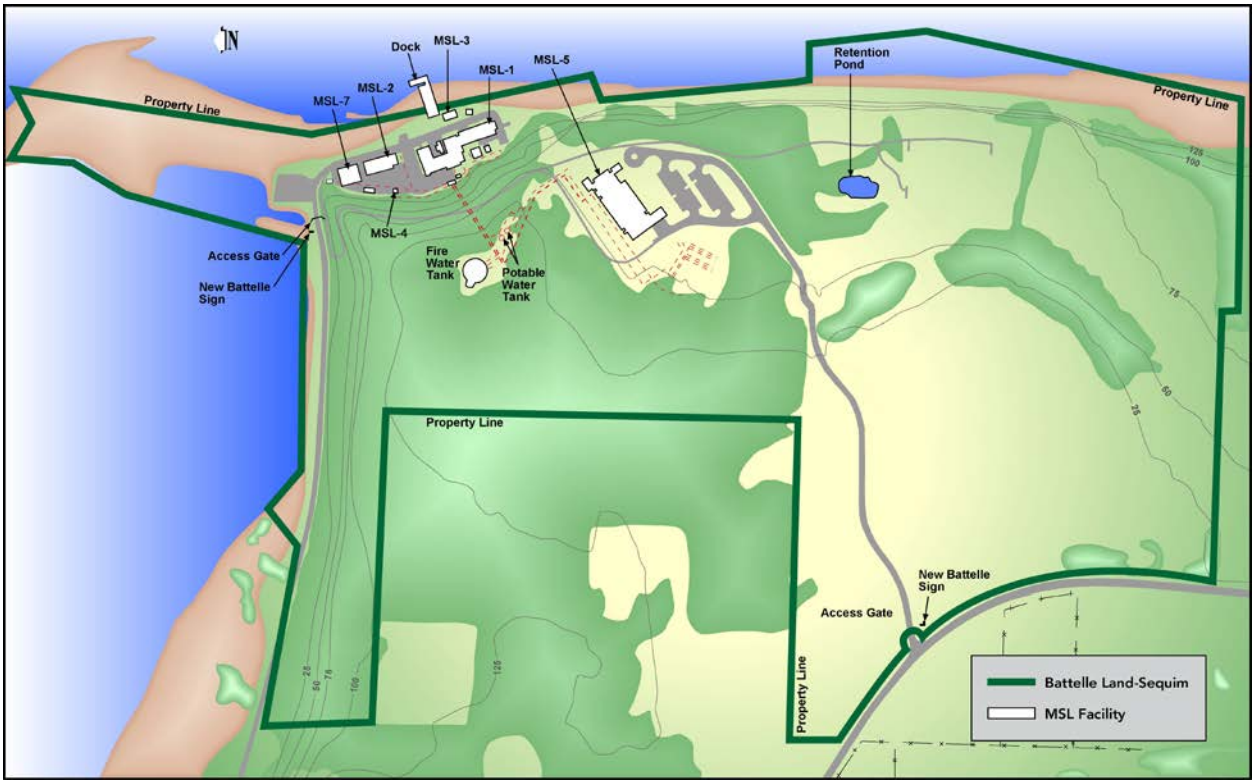


**Figure 1.2.** Battelle Land-Sequim and Marine Sciences Laboratory

**Figure 1.3**. Building MSL-1

**Figure 1.4**. Overhead View of Building MSL-5

# 2.0 Radionuclide Air Emissions

This section describes the two registered MSL emission units and presents emissions estimates for operations during CY 2015.

## 2.1 Major, Minor, and Fugitive Emissions Points

Two nonpoint source minor emission units associated with buildings MSL-1 and MSL-5 are registered with the state of Washington under the Radioactive Air Emissions License (RAEL)-014. 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.

The emission units include EP-MSL-1 and EP-MSL-5 (Figure 1.2). EP-MSL-1 is located on the tidelands, and EP-MSL-5 is located on the upland. The emission unit characteristics are the same for both MSL-1 and MSL-5. These buildings have several locations where radioactive air emissions may originate and exit the building. While they are not fugitive by definition, emissions are fugitive in nature; however, because emissions can come from several points within each building, the emission unit is characterized as a nonpoint source (WAC 2016).

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 2015 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. No credit was taken for abatement controls (e.g., HEPA filtration) at MSL-1 or MSL-5.

**Table 2.1**. 2015 MSL Inventory and Emissions Estimates

| Nuclide | Emission Type | 2015 - EP-MSL-1 [(a)] (Ci) | 2015 - EP-MSL-5 [(a)] (Ci) |
|---|---|---|---|
| H-3 | beta/gamma | - | 1.37E-09 |
| C-14 | beta/gamma | - | 6.41E-10 |
| K-40 | beta/gamma | - | 4.78E-12 |
| Fe-55 | beta/gamma | - | 3.45E-14 |
| Co-57 | beta/gamma | - | 9.46E-15 |
| Co-60 | beta/gamma | - | 1.75E-14 |
| Ni-63 | beta/gamma | - | 3.00E-08 |
| Sr-90 | beta/gamma | - | 8.32E-13 |
| Tc-99 | beta/gamma | - | 1.70E-10 |
| Ru-106 | beta/gamma | - | 4.05E-13 |
| Sb-125 | beta/gamma | - | 5.32E-13 |
| I-125 | beta/gamma | 4.51E-11 | 1.50E-17 |
| I-129 | beta/gamma | - | 1.15E-17 |
| Cs-134 | beta/gamma | - | 3.14E-12 |
| Cs-137 | beta/gamma | - | 3.72E-11 |
| Ba-133 | beta/gamma | - | 2.00E-11 |
| Eu-152 | beta/gamma | - | 6.18E-14 |
| Eu-154 | beta/gamma | - | 1.68E-14 |
| Eu-155 | beta/gamma | | 1.77E-14 |
| Pb-210 | alpha[b] | - | 1.28E-13 |
| Po-208 | alpha | - | 6.98E-10 |
| Po-209 | alpha | - | 1.62E-11 |
| Ra-226 | alpha | - | 2.98E-13 |
| Ra-228 | alpha[b] | - | 4.96E-14 |
| Th-228 | alpha | - | 2.60E-13 |
| Th-230 | alpha | - | 1.53E-13 |
| Th-232 | alpha | - | 3.00E-11 |
| U-234 | alpha | 1.67E-09 | 1.77E-09 |
| U-235 | alpha | 7.63E-11 | 8.12E-11 |
| U-238 | alpha | 1.66E-09 | 1.76E-09 |
| Pu-238 | alpha | - | 8.16E-14 |
| Pu-239 | alpha | - | 3.75E-13 |
| Pu-240 | alpha | - | 3.75E-13 |
| Am-241 | alpha | - | 4.34E-13 |
| **TOTAL (Ci) beta/gamma** | | **4.51E-11** | **3.22E-08** |
| **TOTAL (Ci) alpha** | | **3.41E-09** | **4.36E-09** |

(a) Emissions based on 40 CFR 61, Appendix D methods.
(b) Although Pb-210 and Ra-228 are beta emitters, their decay products include alpha emitters; therefore, they are considered alpha emitters for dose determination.

# 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. A review of radiological assessment needs was published in the Data Quality Objects report (Barnett et al. 2012).

## 3.1 Dose Model and Potential Receptors

The COMPLY Code version 1.6 (Level 4) 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, Appendix E). Input parameters, originally reported by Barnett et al. (2012), were not changed (Table 3.1).

Potential receptor locations for 16 compass directions are provided in Table 3.2, as reported by Barnett et al. (2012), which concluded that continuation of the 190-m source-to-receptor distance used in prior evaluations would result in an overestimate of any expected receptor impacts, but would continue to be used. The nearest location where a member of the public would actually reside or abide (e.g., dwelling, business, school, office) relative to the MSL-1 or MSL-5 emissions locations was determined to be 270 m W or WNW. Given that winds blow predominantly toward the east (see Table 4.3 of Barnett et al. 2012), away from either of these 270-m receptors, an additional level of conservatism is included.

**Table 3.1**. COMPLY Input Parameters

| Parameter | 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) | 8 m |
| Building height (m) | 8 m |
| Stack or vent diameter (m) | NA |
| Volumetric flow rate ($m^3$/s) | NA |
| Distance from source-to-receptor (m) | 190 m[(a)] |
| Building width (m) | 30 m |
| Wind speed (m/s) | 2 m/s |
| Distances to sources of food production (m) | 190 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 receptor distance to land boundary for either MSL-1 or MSL-5; applied to both emission units.
(b) NA(nwr) = not applicable because **n**o **w**ind **r**ose data is used.

**Table 3.2**. Potential MSL MEI Locations

| Direction from MSL-1 or MSL-5 | Smallest distance to BL-S boundary | Smallest Distance to a Receptor Outside BL-S Boundary |
|---|---|---|
| N | - | 1,790 m res[(a)] |
| NNE | - | 39,700 m res[(a)] |
| NE | - | 9,630 m res[(a)] |
| ENE | - | 2,000 m res[(a)] |
| E | - | 1,900 m res[(a)] |
| ESE | - | 2,620 m res |
| SE | - | 3,930 m res |
| SSE | - | 4,470 m res |
| S | 570 m | 640 m res/farm |
| SSW | 630 m | 820 m res; 290 m farm |
| SW | 360 m[(a)] | 420 m res[(a)] |
| WSW | 230 m | 290 m res |
| W | 220 m | 270 m res |
| WNW | 230 m | 270 m res |
| NW | 280 m | 520 m res |
| NNW | - | 1,000 m res/farm |

BL-S = Battelle Land-Sequim (see Figure 1.2).
A dash (-) = a shoreline location where no potential receptor could reside or abide.
res = residence site.
(a) Distance from MSL-1 applied; all other distances are from MSL-5.

## 3.2 Compliance Assessment

The dose standard in 40 CFR 61, Subpart H, applies to radionuclide air emissions, other than radon, from DOE facilities. Dose is estimated as the product of the emission rate (Ci/yr) and unit dose factor (mrem/yr at MEI location per Ci/yr released). Unit dose factors for a number of nuclides are indicated in Appendix B. The Am-241 unit dose factor was applied to all alpha-emitters and the Cs-137 unit dose factor was applied to all beta/gamma emitters, as a conservative measure, except for I-129, which used the nuclide-specific dose factor. For CY 2015, the dose assigned to the MSL MEI overestimates any actual offsite dose. The dose was calculated for a location 190 m (0.12 mi) from the emission point which is the location of a hypothetical boundary receptor. This location is also the point of maximum annual air concentration in an unrestricted area where any member of the public may be (WAC 2007). Sea locations were not considered because the dose factors assume vegetable, milk, and meat production at the receptor location.

The EDE to the 2015 MSL MEI from routine and non-routine point source emissions was 1.1E-04 mrem (1.1E-06 mSv). Table 3.3 shows the relative contributions of each nuclide and facility to the MEI dose. The 2014 MEI estimate was 9E-5 mrem/yr (9E-07 mSv/yr) EDE (Snyder and Barnett 2015).

**Table 3.3**. MSL 2015 Radionuclide Emissions and MEI Dose

| | MSL-1 | MSL-5 | Total |
|---|---|---|---|
| RELEASES (Ci) | | | |
| Beta/gamma | 4.51E-11 | 3.22E-08 | 3.23E-08 |
| Alpha | 3.41E-09 | 4.36E-09 | 7.76E-09 |
| MEI EDE (mrem) | | | |
| Beta/gamma[(a)] | 2.12E-08 | 1.5E-05 | 1.5E-05 |
| Alpha[(b)] | 3.99E-05 | 5.1E-05 | 9.1E-05 |
| **Total (mrem)** | 4.0E-05 | 6.6E-05 | 1.1E-04 |
| DOSE CONTRIBUTION (%) | | | |
| Beta/gamma | 0.1% | 23% | 14% |
| Alpha | 99.9% | 77% | 86% |

(a) Unit dose factor for Cs-137 applied to estimate dose for all nuclide emissions except I-129.
(b) Unit dose factor for Am-241 applied to estimate dose.

Comparing the MSL 2015 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 2015 MEI dose** **0.00011** **mrem/yr**
- Per second natural background radiation 0.0000098 mrem/sec

# 4.0 Supplemental Information

This section provides supplemental information related to MSL radionuclide air emissions in 2015. 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 mi (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 mi of MSL and is more than 20 mi from MSL.

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

| Population at Indicated Distance[(a)] | Distance (mi) | 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 collective dose was estimated assuming the total 2015 curies released (Table 3.3) dispersed in the single direction. The maximum collective dose was determined to result from dispersion to the west, which only contains U.S. populations. The MEI dose (1.1E-4 mrem) was multiplied by a population weighted air concentration in the direction of maximum collective impact for a collective dose of 1.2E-4 person-rem. If the release were dispersed only to the maximum Canadian sector (NNW), the maximum estimated Canadian collective dose would be 4.9E-5 person-rem. Dispersal towards 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 2015.

# 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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WAC—Washington Administrative Code. 2016. *Radiation Protection – Air Emissions*. WAC-246-247, Statutory Law Committee, Olympia, WA.

Zuljevic N, TE Seiple, SF Snyder. 2016. *Battelle Land–Sequim Regional Population*. PNNL-25305, Pacific Northwest National Laboratory, Richland, WA.

# Appendix A

# List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2015

# Appendix A: List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2015

**Table A.1.** List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2015

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ac-225 | Bk-249 | Cs-134m | Ho-166 | Mn-56 | Pd-109 | Rh-102 | Ta-180 | U-232 |
| Ac-227 | Bk-250 | Cs-135 | Ho-166m | Mo-93 | Pm-143 | Rh-102m | Ta-182 | U-233 |
| Ac-228 | Br-82 | Cs-136 | I-122 | Mo-99 | Pm-144 | Rh-103m | Ta-182m | U-234 |
| Ag-108 | Br-82m | Cs-137 | I-123 | Mo-103 | Pm-145 | Rh-104 | Ta-183 | U-235 |
| Ag-108m | Br-83 | Cs-138 | I-125 | Mo-104 | Pm-146 | Rh-105 | Tb-157 | U-235m |
| Ag-109m | Br-84 | Cs-139 | I-126 | Mo-105 | Pm-147 | Rh-105m | Tb-158 | U-236 |
| Ag-110 | Br-84m | Cs-140 | I-128 | N-13 | Pm-148 | Rh-106 | Tb-160 | U-237 |
| Ag-110m | Br-85 | Cs-141 | I-129 | Na-22 | Pm-148m | Rn-219 | Tb-161 | U-238 |
| Ag-111 | C-11 | Cu-64 | I-130 | Na-24 | Pm-149 | Rn-220 | Tc-95 | U-239 |
| Al-26 | C-14 | Cu-66 | I-130m | Na-24m | Pm-151 | Rn-222 | Tc-95m | U-240 |
| Al-28 | C-15 | Cu-67 | I-131 | Nb-91 | Po-208 | Rn-224 | Tc-97 | V-48 |
| Am-240 | Ca-41 | Dy-159 | I-132 | Nb-91m | Po-209 | Ru-97 | Tc-97m | V-49 |
| Am-241 | Ca-45 | Dy-165 | I-132m | Nb-92 | Po-210 | Ru-103 | Tc-98 | W-181 |
| Am-242 | Ca-47 | Dy-169 | I-133 | Nb-93m | Po-211 | Ru-105 | Tc-99 | W-185 |
| Am-242m | Cd-107 | Er-169 | I-133m | Nb-94 | Po-212 | Ru-106 | Tc-99m | W-187 |
| Am-243 | Cd-109 | Er-171 | I-134 | Nb-95 | Po-213 | S-35 | Tc-101 | W-188 |
| Am-245 | Cd-111m | Es-254 | I-134m | Nb-95m | Po-214 | Sb-122 | Tc-103 | Xe-122 |
| Am-246 | Cd-113 | Eu-150 | I-135 | Nb-97 | Po-215 | Sb-124 | Tc-106 | Xe-123 |
| Ar-37 | Cd-113m | Eu-152 | In-106 | Nb-97m | Po-216 | Sb-125 | Te-121 | Xe-125 |
| Ar-39 | Cd-115 | Eu-152m | In-111 | Nb-98 | Po-218 | Sb-126 | Te-121m | Xe-127 |
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| As-77 | Ce-141 | F-18 | In-115m | Nd-147 | Pu-236 | Sc-46 | Te-127m | Xe-133m |
| At-217 | Ce-142 | Fe-55 | In-116 | Ni-56 | Pu-237 | Sc-47 | Te-129 | Xe-135 |
| Au-193 | Ce-143 | Fe-59 | In-116m | Ni-57 | Pu-238 | Se-75 | Te-129m | Xe-135m |
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| Au-195 | Cf-249 | Fr-223 | In-117m | Ni-63 | Pu-240 | Se-79m | Te-131m | Xe-138 |
| Au-196 | Cf-250 | Ga-67 | Ir-192 | Ni-65 | Pu-241 | Si-31 | Te-132 | Xe-139 |
| Au-198 | Cf-251 | Ga-68 | K-40 | Np-235 | Pu-242 | Si-32 | Te-133 | Y-88 |
| Au-198m | Cf-252 | Ga-70 | K-42 | Np-236 | Pu-243 | Sm-145 | Te-133m | Y-90 |
| Au-199 | Cl-36 | Ga-72 | Kr-81 | Np-237 | Pu-244 | Sm-146 | Te-134 | Y-90m |
| Ba-131 | Cm-241 | Gd-148 | Kr-81m | Np-238 | Pu-246 | Sm-147 | Th-227 | Y-91 |
| Ba-133 | Cm-242 | Gd-149 | Kr-83m | Np-239 | Ra-223 | Sm-148 | Th-228 | Y-91m |
| Ba-133m | Cm-243 | Gd-151 | Kr-85 | Np-240 | Ra-224 | Sm-151 | Th-229 | Y-92 |
| Ba-137m | Cm-244 | Gd-152 | Kr-85m | Np-240m | Ra-225 | Sm-153 | Th-230 | Y-93 |
| Ba-139 | Cm-245 | Gd-153 | Kr-87 | O-15 | Ra-226 | Sm-157 | Th-231 | Yb-164 |
| Ba-140 | Cm-246 | Gd-159 | Kr-88 | O-19 | Ra-228 | Sn-113 | Th-232 | Yb-169 |
| Ba-141 | Cm-247 | Ge-68 | Kr-89 | Os-191 | Rb-81 | Sn-117m | Th-233 | Yb-175 |
| Ba-142 | Cm-248 | Ge-71 | Kr-90 | P-32 | Rb-82 | Sn-119m | Th-234 | Yb-177 |
| Ba-143 | Cm-250 | Ge-71m | La-137 | P-33 | Rb-83 | Sn-121 | Ti-44 | Zn-65 |
| Be-7 | Co-56 | Ge-75 | La-138 | Pa-231 | Rb-84 | Sn-121m | Ti-45 | Zn-69 |
| Be-10 | Co-57 | Ge-77 | La-140 | Pa-233 | Rb-86 | Sn-123 | Ti-51 | Zn-69m |
| Bi-207 | Co-58 | Ge-77m | La-141 | Pa-234 | Rb-87 | Sn-125 | Tl-201 | Zr-88 |
| Bi-208 | Co-60 | H-3 | La-142 | Pa-234m | Rb-88 | Sn-126 | Tl-204 | Zr-89 |
| Bi-210 | Co-60m | Hf-175 | La-144 | Pb-209 | Rb-89 | Sr-85 | Tl-206 | Zr-93 |
| Bi-210m | Cr-49 | Hf-178m | Lu-177 | Pb-210 | Rb-90 | Sr-87m | Tl-207 | Zr-95 |
| Bi-211 | Cr-51 | Hf-179m | Lu-177m | Pb-211 | Rb-90m | Sr-89 | Tl-208 | Zr-97 |
| Bi-212 | Cr-55 | Hf-181 | Mg-27 | Pb-212 | Re-186 | Sr-90 | Tl-209 | Zr-98 |
| Bi-213 | Cs-131 | Hf-182 | Mg-28 | Pb-214 | Re-187 | Sr-91 | Tm-168 | Zr-99 |
| Bi-214 | Cs-132 | Hg-203 | Mn-52 | Pd-103 | Re-188 | Sr-92 | Tm-170 | Zr-100 |
| Bk-247 | Cs-134 | Ho-163 | Mn-54 | Pd-107 | Rh-101 | Ta-179 | Tm-171 | |

# Appendix B

# COMPLY Unit Dose Factors

# Appendix B: COMPLY Unit Dose Factors

As originally reported in Barnett et al. 2012, COMPLY v1.6 was used to determine unit-release dose factors (UDFs), which represent impacts to a hypothetical receptor 190 m from the emission unit with an assumed 2 m/s wind speed and wind blowing toward the receptor 25% of the time. These assumptions are based on calculations of COMPLY v1.6 at Level 4 with no wind rose used. 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). Several nuclides ($^{133}$Ba, $^{22}$Na, $^{210}$Pb, $^{3}$H, and $^{14}$C) are footnoted to indicate that only one option was available (EPA 1989). Additionally, the more conservative (overestimating) classification was applied to uranium. UDFs for radionuclides either in current inventory or previously used at MSL are presented.

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

| Nuclide | COMPLY Solubility Class | Unit Dose Factor (mrem EDE per Ci/yr released) |
|---|---|---|
| **$^{241}$Am**(a) | W | 11700 |
| $^{133}$Ba(b) | D | 135 |
| $^{14}$C(c) | "1" | 1.5 |
| $^{109}$Cd | W | 5.5 |
| $^{57}$Co | W | 4.8 |
| $^{60}$Co | W | 426 |
| $^{137}$Cs(a) | D | 469 |
| $^{154}$Eu | W | 345 |
| $^{155}$Eu | W | 13.3 |
| $^{3}$H(b) | V | 0.004 |
| $^{125}$I | D | 84.5 |
| $^{129}$I | D | 1250 |
| $^{54}$Mn | W | 27.2 |
| $^{22}$Na(b) | D | 234 |
| $^{63}$Ni | W | 0.3 |
| **$^{210}$Pb**(b) | D | 1100 |
| **$^{238}$Pu** | W | 10300 |
| **$^{239}$Pu** | W | 11200 |
| $^{106}$Ru | W | 13.9 |
| $^{90}$Sr(d) | Y | 211 |
| $^{99}$Tc | W | 32.7 |
| **$^{234}$U** | Y | 3450 |
| **$^{235}$U** | Y | 3470 |
| **$^{238}$U** | Y | 3110 |
| **Natural U**(e) | Y | 3290 |

**Bold font** = alpha-emitting nuclides. All others are beta/gamma emitters.
(a) $^{241}$Am is the surrogate alpha emitter for those not specifically listed; $^{137}$Cs is the surrogate beta emitter for those not specifically listed.
(b) The solubility class listed is the only option available in COMPLY v1.6.
(c) Default class of COMPLY v1.6 used.
(d) Solubility class W is preferred, but not an option. Class Y was used as an overestimating assumption.
(e) Determined from natural uranium mass fractions: 0.000055 $^{234}$U; 0.0072 $^{235}$U; 0.9928 $^{238}$U (DOE 2009).

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