PNNL-22342-6

Pacific Northwest NATIONAL LABORATORY

Department of Energy – Office of Science
Pacific Northwest National Laboratory

Marine Sciences Laboratory Radionuclide Air Emissions Report for Calendar Year 2017

SF Snyder
JM Barnett

May 2018

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 (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 2017 was 1.6E-04 mrem (1.6E-6 mSv). No non-routine emissions occurred in 2017. The MSL is in compliance with the federal and state 10 mrem/yr standard.

An update to the MEI dose indicated in the prior report is included, that indicates a more precise, less-over-estimating, dose estimate. The CY2016 emission year MEI dose was reported to be 5.7E-4 mrem (5.7E-6 mSv) and is now updated to a more precise 1.6E-4 mrem (1.6E-6 mSv) dose.

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-22342-6

DOE-SC
Pacific Northwest National Laboratory
Marine Sciences Laboratory
Radionuclide Air Emissions Report
Calendar Year 2017

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

6/4/18
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., 1×10^{-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 Office of Science (DOE-SC) 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) 2017.

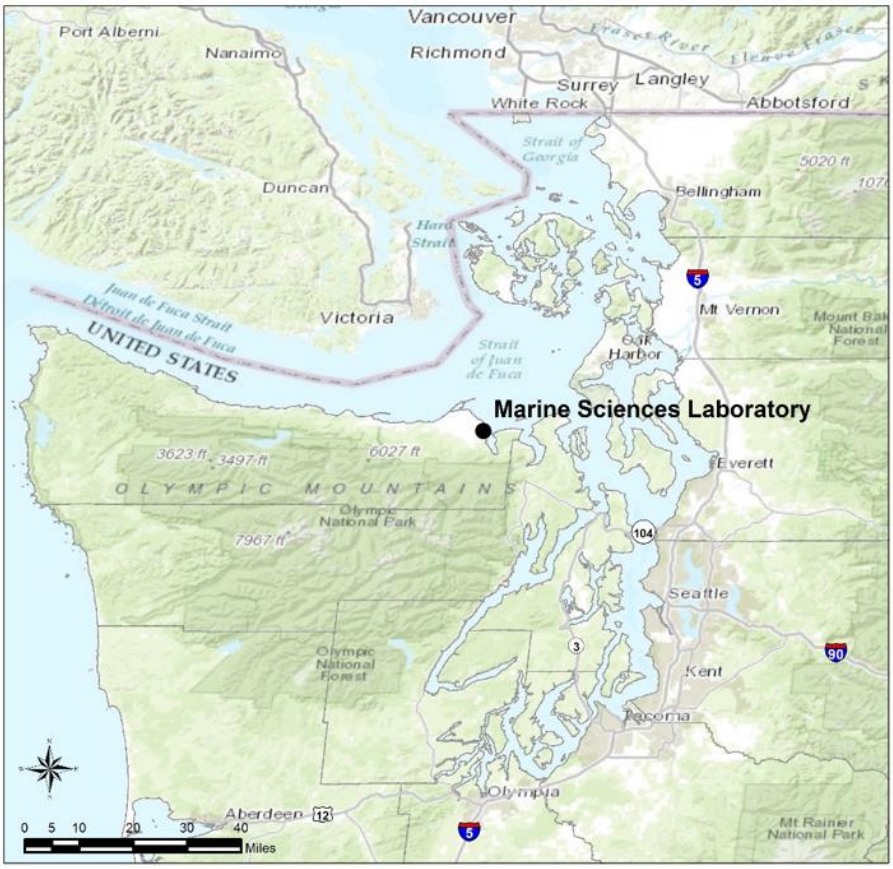

Figure 1.1. MSL in Northwestern Washington State

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 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.

Emission points are located in two buildings: MSL-1 and MSL-5. MSL-1 (Figure 1.3) contains laboratories 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. MSL-5 (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.

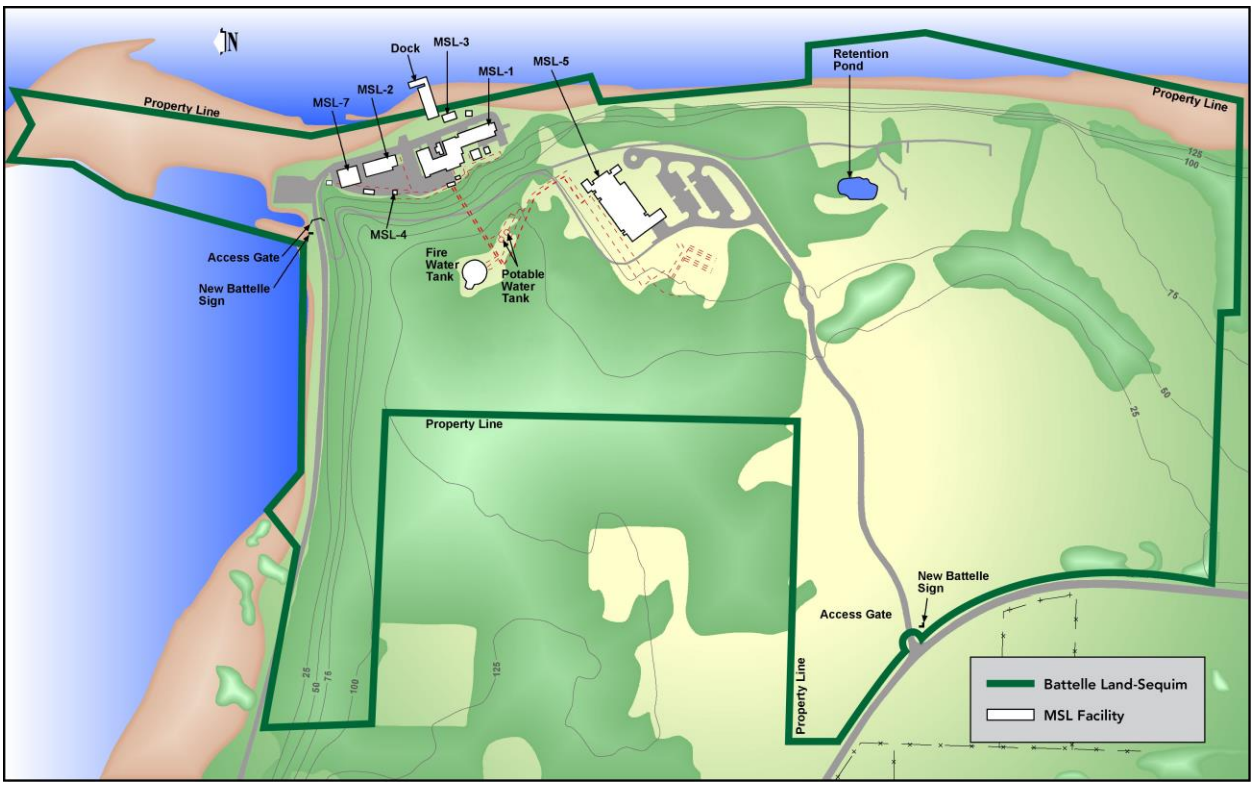

Figure 1.2. Battelle Land-Sequim and Marine Sciences Laboratory

Figure 1.3. MSL-1 Building

Figure 1.4. MSL-5 Building

2.0 Radionuclide Air Emissions

This section describes the two registered MSL emission units and presents emissions estimates for operations during CY 2017.

2.1 Major, Minor, and Fugitive Emissions Points

Two nonpoint source minor emission units associated with 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 2017 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. 2017 MSL Emissions Estimates

Nuclide	2017 – EP-MSL-1[(a)] (Ci)	2017 – EP-MSL-5[(a)] (Ci)
H-3	-	7.0E-11
C-14	-	2.5E-13
K-40	5.7E-12	4.8E-12
Fe-55	-	3.5E-14
Co-57	-	9.5E-15
Co-60	-	1.2E-13
Sr-90	1.5E-12	8.3E-13
Tc-99	-	3.0E-10
Ru-106	7.6E-13	4.1E-13
Sb-125	1.0E-12	5.4E-13
I-125	1.0E-06	-
I-129	2.3E-17	2.4E-15
Cs-134	6.3E-12	3.1E-12
Cs-137	7.1E-11	3.7E-11
Eu-152	-	6.2E-14
Eu-154	-	1.5E-13
Eu-155	-	1.8E-14
Pb-210	-	1.3E-13
Po-208	-	7.0E-10
Po-209	-	1.4E-11
Ra-226	2.7E-13	3.0E-13
Ra-228	-	5.0E-14
Th-228	1.4E-13	2.6E-13
Th-230	-	1.5E-13
Th-232	2.8E-13	2.6E-13
U-233	-	6.7E-15
U-234	7.0E-09	4.8E-09
U-235	3.2E-10	2.2E-10
U-238	7.0E-09	4.7E-09
Pu-238	4.8E-16	8.2E-14
Pu-239	2.0E-15	3.8E-13
Pu-240	2.0E-15	3.7E-13
Pu-241	-	4.7E-14
Am-241	8.8E-16	4.3E-13
TOTAL (Ci)	**1.0E-06**	**1.1E-08**

(a) 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. 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 1.7 (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. The emissions from Table 2.1 resulted in the MEI doses reported in Table 3.3. In order to report radionuclide-specific doses, dose were 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 are indicated in Appendix B. Po-208 and Po-209 are not available in COMPLY 1.7, therefore the Po-210 was used as a surrogate with twice and emission rate assumption to overestimate the actual dose used for the emissions. For CY 2017, the dose assigned to the MSL MEI overestimates any actual offsite dose. The dose was calculated for a location 190 m (0.12 miles) 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 2017 MSL MEI from routine and non-routine point source emissions was 1.6E-04 mrem (1.6E-06 mSv). Table 3.3 shows the relative contributions of each nuclide and facility to the MEI dose. The 2016 MEI estimate (see Section 5.0) was 1.6E-4 mrem/yr (1.6E-06 mSv/yr) EDE (also see Snyder and Barnett 2017).

Table 3.3. MSL 2017 MEI Dose

Nuclide	MSL-1 2017 MEI Dose (mrem)	MSL-5 2017 MEI Dose (mrem)	Total 2017 MEI Dose (mrem)
H-3	-	2.8E-13	2.8E-13
C-14	-	3.7E-13	3.7E-13
K-40	2.0E-09	1.7E-09	3.6E-09
Fe-55	-	1.4E-14	1.4E-14
Co-57	-	4.5E-14	4.5E-14
Co-60	-	5.2E-11	5.2E-11
Sr-90	3.1E-10	1.8E-10	4.8E-10
Tc-99	-	9.8E-09	9.8E-09
Ru-106	1.1E-11	5.6E-12	1.6E-11
Sb-125	5.1E-11	2.6E-11	7.7E-11
I-125	8.5E-05	-	8.5E-05
I-129	2.9E-14	3.0E-12	3.1E-12
Cs-134	1.2E-09	5.9E-10	1.8E-09
Cs-137	3.3E-08	1.7E-08	5.1E-08
Eu-152	-	2.8E-11	2.8E-11
Eu-154	-	5.2E-11	5.2E-11
Eu-155	-	2.4E-13	2.4E-13
Pb-210	-	1.4E-10	1.4E-10
Po-208[(a)]	-	7.7E-07	7.7E-07
Po-209[(a)]	-	1.5E-08	1.5E-08
Ra-226	8.3E-10	9.2E-10	1.7E-09
Ra-228	-	2.9E-11	2.9E-11
Th-228	1.3E-09	2.3E-09	3.5E-09
Th-230	-	1.3E-09	1.3E-09
Th-232	1.2E-08	1.1E-08	2.3E-08
U-233	-	2.4E-11	2.4E-11
U-234	2.4E-05	1.6E-05	4.1E-05
U-235	1.1E-06	7.5E-07	1.9E-06
U-238	2.2E-05	1.5E-05	3.6E-05
Pu-238	4.9E-12	8.4E-10	8.5E-10
Pu-239	2.3E-11	4.2E-09	4.2E-09
Pu-240	2.3E-11	4.2E-09	4.2E-09
Pu-241	-	1.0E-11	1.0E-11
Am-241	1.0E-11	5.1E-09	5.1E-09
TOTAL Dose Contribution	**1.3E-04 mrem 80%**	**3.3E-05 mrem 20%**	**1.6E-04 mrem 100%**

(a) Po-208 and Po-209 are unavailable in COMPLY 1.7; Emission assigned as Po-210 with two times the release rate (Ci) an over-estimating assumption.

Comparing the MSL 2017 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 2017 MEI dose**	**0.00016**	**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 2017. 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 2017 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 (1.6E-4 mrem) was multiplied by a population weighted air concentration in the direction of maximum collective impact for a collective dose of 1.8E-4 person-rem. If the release were dispersed only to the maximum Canadian sector (NNW), the maximum estimated Canadian collective dose would be 7.2E-5 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 2017.

5.0 Corrigendum for CY2016 Emissions Report

The dose reported for the MSL-1 emission unit in last year's 40 CFR Part 61, Subpart H, compliance report from emissions in CY2016 was 5.1E-04 mrem (5.1E-06 mSv) , a value well below the 10 mrem (0.1 mSv) TED compliance threshold. However, it was just above the RAEL-014 license value of 4.37E-04 mrem (4.37E-06 mSv) for this emission unit. As required for the WDOH, this corrigendum presents the more precisely calculated dose estimate from CY2016 emissions of MSL-1, which indicates that the dose from this emission unit does fall below the license value for the emission unit.

The Snyder and Barnett 2017 dose for MSL-1 was calculated using conservative (over-estimating), simplifying assumptions regarding the dose from the specific radionuclides emitted. Under the simplifying assumptions applied, results are typically below permit limits.

During 2016 MSL-1 emitted I-125 and U isotopes (Table 5.1). The I-125 (1.0E-6 Ci) is the only beta/gamma nuclide. In Snyder and Barnett 2017, the Cs-137 dose factor was used to simplify beta/gamma dose calculations when a long list of beta-/gamma-emitting nuclides are included in the source term from a facility. MSL-1 does not have a long list of beta/gamma emissions, but the Cs-137 dose factor was used, to be consistent with MSL-5 calculations; MSL-5 had a long list of beta-/gamma-emitting nuclides. In the same manner, Am-241 was used as a surrogate for alpha-emitting nuclide dose calculations. The Am-241 dose factor was used for all MSL-1 uranium isotope emissions.

A COMPLY 1.7.1 case for the MSL-1 emissions was completed, with a total dose result of 9.6E-05 mrem for the MEI. Table 5.1 indicates the MSL-1 dose results using both the surrogate nuclides and the nuclide-specific cases. The 9.6E-05 mrem (9.6E-07 mSv) MSL-1 dose from the nuclide-specific case is below the license threshold of 4.37E-4 mrem (4.37E-6 mSv).

Adding the nuclide-specific dose result for MSL-1 and the surrogate-nuclide dose of MSL-5 (6.2E-05 mrem) would result in a total dose to the 2106 MSL MEI of 1.6E-4 mrem (1.6E-6 mSv) TED, about a third of the 5.7E-4 mrem (5.7E-6 mSv) MEI dose reported in Snyder and Barnett 2017.

Table 5.1. Corrigenda for MSL-1 Dose from CY2016 Emissions

Nuclide	Emission type	MSL-1 2016 Release (Ci)	MSL-1 2016 Surrogate-nuclide Method Dose (mrem)	MSL-1 2016 Nuclide-specific Dose (mrem)
I-125	beta/gamma	1.00E-06	4.69E-04	8.5E-05
U-234	alpha	1.67E-09	1.95E-05	5.8E-06
U-235	alpha	7.63E-11	8.93E-07	2.6E-07
U-238	alpha	1.66E-09	1.94E-05	5.2E-06
Total Dose			**5.1E-04 mrem**	**9.6E-05 mrem**

Comparing the 2016 MSL 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 2016 MEI dose (Snyder and Barnett 2017)**	**0.00057**	**mrem/yr**
• **MSL 2016 MEI updated dose estimate**	**0.00016**	**mrem/yr**
• Per second natural background radiation	0.0000098	mrem/sec

The collective dose estimate of Snyder and Barnett 2017 would also decrease as a result of nuclide-specific dose results from MSL-1. The collective dose estimate from all 2016 MSL emissions of 6.4E-4 person-rem (Snyder and Barnett 2017) would decrease to 1.8E-4 person-rem.

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Appendix A

List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2017

Appendix A: List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2017

Table A.1. List of Radioactive Materials Handled or Potentially Handled, or Authorized for Use at MSL in 2017

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

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 COMPLY calculations 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. Additional UDFs have been added using either COMPLY v1.6 or v1.7. As indicated in the following table, COMPLY default inhalation solubility class are used as simplifying, overestimating assumptions for dose determination (see solubility class preferences in Snyder and Rokkan (2016), Table 3.1).

Table B.1. MSL Unit Dose Factors

Nuclide	Footnote	COMPLY Solubility Class	Unit Dose Factor (mrem EDE per Ci/yr released)
^{241}Am		W	11700
^{133}Ba	a	D	135
^{14}C	b	"1"	1.5
^{109}Cd		W	5.5
^{57}Co		W	4.8
^{60}Co		W	426
^{134}Cs		D	189
^{137}Cs		D	469
^{152}Eu		W	445
^{154}Eu		W	345
^{155}Eu		W	13.3
^{55}Fe		D	0.4
^{3}H	a	V	0.004
^{125}I		D	84.5
^{129}I		D	1250
^{40}K	a	D	346
^{54}Mn		W	27.2
^{22}Na	a	D	234
^{63}Ni		W	0.3
^{210}Pb	a	D	1100
^{210}Po	c	D	550
^{238}Pu		W	10300
^{239}Pu		W	11200
^{240}Pu		W	11200
^{241}Pu		W	217
^{226}Ra		W	3080
^{228}Ra		W	592
^{106}Ru		W	13.9
^{125}Sb		W	48.6
^{90}Sr	d	Y	211
^{99}Tc		W	32.7
^{228}Th		Y	8810
^{230}Th	e	W	8400
^{232}Th	e	W	43700
^{233}U	d	Y	3530
^{234}U	d	Y	3450
^{235}U	d	Y	3470
^{238}U	d	Y	3110
Natural U	f	Y	3290

Bold font = alpha-emitting nuclides. All others are beta/gamma emitters.
(a) The solubility class listed is the only option available in COMPLY v1.6 or v1.7.
(b) Default class of COMPLY v1.6 or v1.7 used.
(c) ^{210}Po can be used as a surrogate for ^{208}Po and ^{209}Po, which are not available in COMPLY v1.6 or v1.7. Solubility class W is preferred, but the default class D used as an over-estimating) assumption.
(d) Solubility class W is preferred, but the default class Y was used as an overestimating assumption.
(e) Solubility class S is preferred, but the default class W used as an overestimating assumption.
(f) Determined from natural uranium mass fractions: 0.000055 ^{234}U; 0.0072 ^{235}U; 0.9928 ^{238}U (DOE 2009).

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