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Lawrence Berkeley National Laboratory Radionuclide Air Emission Report for 2014

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Ernest Orlando Lawrence Berkeley National Laboratory
Berkeley, CA

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U.S. Department of Energy

Radionuclide Air Emission Report for 2014

(in compliance with 40 CFR 61, Subpart H)

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Acronyms

ALS	Advanced Light Source
CAP88-PC	Clean Air Act Assessment Package 1988 for Personal Computers, EPA-approved dose calculation software
CFR	Code of Federal Regulations
COMPLY	EPA-approved dose calculation software
DOE	U. S. Department of Energy
EPA	U. S. Environmental Protection Agency
HEPA	High-efficiency particulate air
JBEI	Joint BioEnergy Institute
LBNL	Lawrence Berkeley National Laboratory
LHS	Lawrence Hall of Science
LOASIS	Lasers and Optical Accelerator Systems Integrated Studies
MEI	Maximally exposed individual
NESHAP	National Emission Standards for Hazardous Air Pollutants
TEDA-DAC	Triethylene-diamine-doped activated carbon
UC	University of California

Preface

As a U.S. Department of Energy (DOE) facility whose operations involve the use of radionuclides, Lawrence Berkeley National Laboratory (LBNL), also referred to as Berkeley Lab, is subject to U.S. Environmental Protection Agency (EPA) radioactive air emission regulations that are found in the Code of Federal Regulations (CFR) Title 40, Part 61, National Emission Standards for Hazardous Air Pollutants (NESHAP) (EPA 1989a). Subpart H of this regulation, *National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities* (subsequently referred to as NESHAP), establishes standards for exposure of the public to radionuclides (other than radon) released from DOE facilities. This regulation limits the emission of radionuclides to the ambient air from DOE facilities. Such emissions may not exceed amounts that would cause any member of the public to receive an effective dose equivalent (subsequently referred to as dose) of 10 millirem/year (mrem/yr) (0.1 millisievert/year [mSv/yr]).

Under the NESHAP regulations, DOE facilities are required to submit an annual report each year. The NESHAP regulation specifies the content of the report and DOE provides further guidance (DOE 1994). This document is Berkeley Lab's annual report of radionuclide air emissions for 2014 and meets the NESHAP requirements for reporting. This report can be found on the Berkeley Lab website at http://www2.lbl.gov/ehs/esg/Reports/tableforreports.shtml .

Executive Summary

Berkeley Lab operates facilities that are subject to the EPA radioactive air emission regulations in 40 CFR 61, Subpart H, which limits doses from airborne emissions to less than 10 mrem/yr (0.1 mSv/yr) (EPA 1989a). In 2014, all Berkeley Lab facilities were minor sources of radionuclides resulting in a potential dose much less than the EPA dose standard. There were no diffuse sources or unplanned airborne radionuclide emissions from Berkeley Lab operations. Emissions from minor sources were measured by sampling or calculated based on quantities used, received for use, or produced during the year in Lab facilities. Using these measured and calculated emissions, Berkeley Lab personnel applied the EPA-approved computer codes CAP88-PC and COMPLY to calculate doses to the maximally exposed individual (MEI) at offsite points where there is a residence, school, business, or office. As radionuclides are used at three noncontiguous locations (the main site, Berkeley West Biocenter, and Joint BioEnergy Institute), three different MEIs were identified.

At the Berkeley Lab main site, the potential dose from all sources in 2014 was 2.7×10^{-2} mrem/yr (2.7×10^{-4} mSv/yr) to the MEI, well below the 10 mrem/yr (0.1 mSv/yr) dose standard. The location of this MEI is at the Lawrence Hall of Science, a public science museum about 1500 feet (ft) (460 meters [m]) east of Berkeley Lab's Building 56. The estimated collective dose to persons living within 50 miles (mi) (80 kilometers [km]) of the Berkeley Lab main site was 3.2×10^{-1} person-rem (3.2×10^{-3} person-Sv) attributable to Berkeley Lab's airborne emissions in 2014. Potential doses to the public are considered to be a conservative or upper bound estimate as the EPA-approved software assumes the MEI to be present 24 hours a day for the entire year, eating meat and vegetables grown nearby, and drinking water from local wells presumed to be contaminated with deposited airborne radionuclides. Additionally, annual fluorine-18 (^{18}F) emissions from Building 56 include false positive measurements caused by ^{18}F adsorbing on to the real-time detectors and continuing to decay, emitting detectable positrons.

At the Berkeley West Biocenter (Building 977), the potential dose from Berkeley Lab operations in 2014 was 1.6×10^{-4} mrem/yr (1.6×10^{-6} mSv/yr) to the MEI, well below the 10 mrem/yr (0.1 mSv/yr) dose standard. The location of this MEI is in the same building as the source of radioactive air emissions, about 98 ft (30 m) from the point where emissions from Berkeley Lab operations are released. The estimated collective dose to persons living within 50 mi (80 km) was 3.9×10^{-6} person-rem (3.9×10^{-8} person-Sv) attributable to Berkeley Lab's airborne emissions from Building 977 in 2014.

At the Joint BioEnergy Institute (Building 978), the potential dose from Berkeley Lab operations in 2014 was 1.3×10^{-3} mrem/yr (1.3×10^{-5} mSv/yr) to the MEI, well below the 10 mrem/yr (0.1 mSv/yr) dose standard. The location of this MEI is in the same building as the source of radioactive air emissions, about 62 ft (19 m) from the point where emissions from Berkeley Lab operations are released. The estimated collective dose to persons living within 50 mi (80 km) was 4.0×10^{-6} person-rem (4.0×10^{-8} person-Sv) attributable to Berkeley Lab's airborne emissions from Building 978 in 2014.

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Facility Information

Lawrence Berkeley National Laboratory (LBNL), also known as Berkeley Lab, was founded by Ernest O. Lawrence in 1931. Lawrence invented a unique particle accelerator, called a cyclotron, ushering in a new era in the study of subatomic particles, and receiving the Nobel Prize in physics for it in 1939. Through his work, Lawrence launched the modern era of multidisciplinary team science. To this day, Berkeley Lab continues the tradition of multidisciplinary scientific teams working together to solve global problems in human health, technology, energy, and the environment.

Berkeley Lab supports work in such diverse fields as genomics, physical biosciences, alternative fuels, nanoscience, life sciences, fundamental physics, accelerator physics and engineering, energy conservation technology, and materials science. Through its fundamental research in these fields, Berkeley Lab has achieved international recognition for its leadership and has made numerous contributions to national programs. Berkeley Lab's research embraces the following concepts to align with the Department of Energy (DOE) mission:

- Explore the complexity of energy and matter
- Advance the science needed to attain abundant clean energy
- Understand energy impacts on our living planet
- Provide extraordinary tools for multidisciplinary research

1.1 Site Description

Berkeley Lab is located about 3 mi (5 km) east of San Francisco Bay (see Figure 1-1) on land owned by the University of California (UC). The main site is situated on approximately 202 acres provided by the University of California on long-term lease to the Department of Energy for many of the buildings and facilities. Included in what is considered the main site is Building 1 (Donner Lab), which is located on the eastern side of the adjacent UC Berkeley campus, within walking distance of Berkeley Lab.

The main site lies in the hills above UC Berkeley campus on the ridges and draws of Blackberry Canyon (which forms much of the western part of the site) and adjacent Strawberry Canyon (which forms much of the southern part of the site). Elevations across the site range from 450 to 1,150 ft (135 to 350 m) above sea level. The western portion of the site lies in Berkeley, while the eastern portion lies in Oakland. The entire site is located within Alameda County (see Figure 1-2). The population of Berkeley is estimated at 113,000 and that of Oakland is approaching 391,000 (MTC/ABAG 2010).

Berkeley Lab also leases space at two nearby, off-site buildings where radionuclides are used in biological research. The Berkeley West Biocenter (Building 977) is located at 717 Potter St. in Berkeley, and the Joint BioEnergy Institute (JBEI, Building 978) is located at 5885 Hollis St. in Emeryville (see Figure 1-2). Elevations at these buildings range from 35 to 50 ft (11 to 15 m) above sea level. Emeryville is a small community between Berkeley and Oakland with a population of 10,100 (MTC/ABAG 2010).

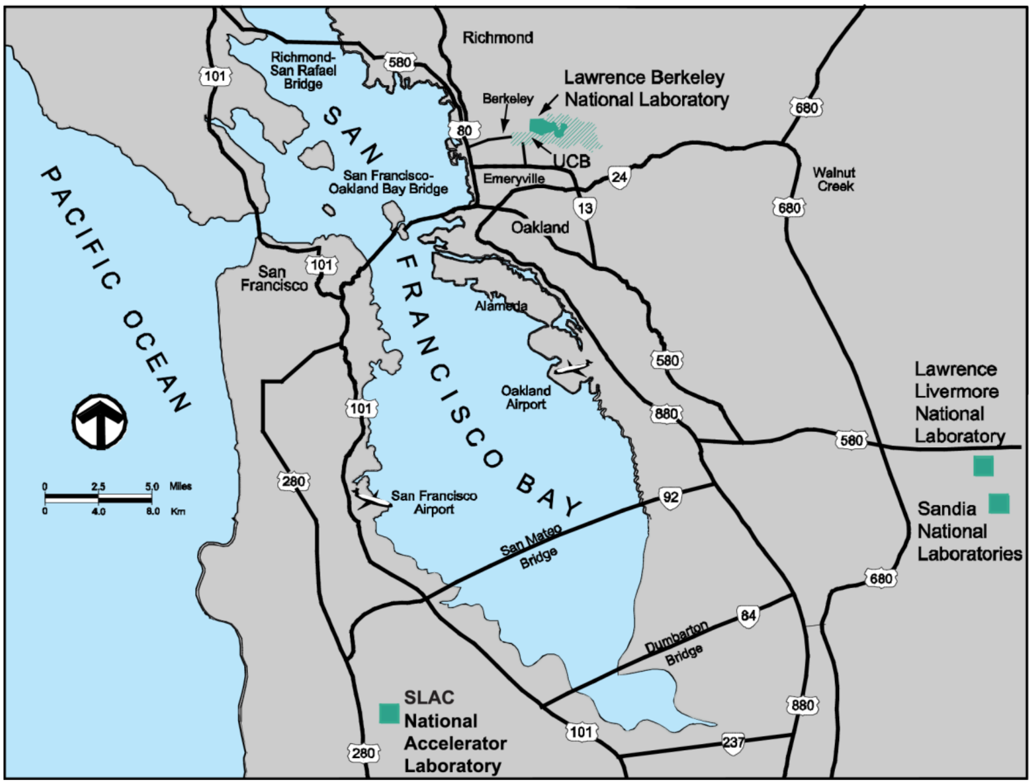

Figure 1-1 San Francisco Bay Area Map

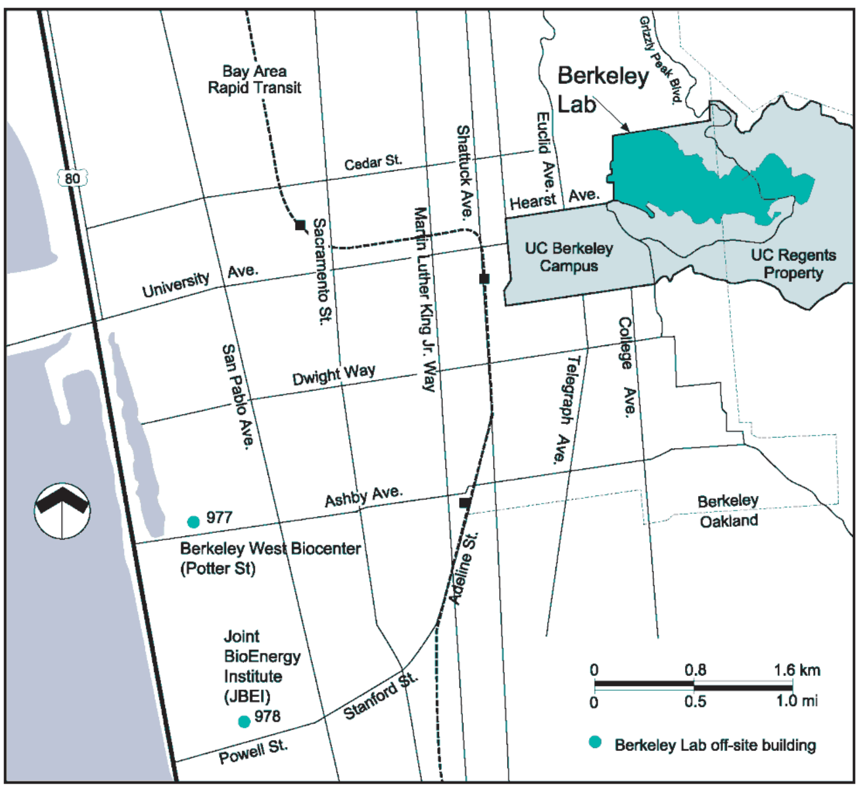

Figure 1-2 Vicinity Map

Adjacent land use consists of residential, institutional, and recreational areas. The area to the south and east of the main site, which is UC land, is maintained largely in a natural or undeveloped state but includes UC Berkeley's Strawberry Canyon Recreational Area and Botanical Garden. To the northeast are the university's Lawrence Hall of Science, Space Sciences Laboratory, and Mathematical Sciences Research Institute. Berkeley Lab is bordered to the north by a residential neighborhood of low-density, single-family homes and to the west by the UC Berkeley campus as well as multi-unit dwellings, student residence halls, and private homes. This area to the west of Berkeley Lab is highly urbanized.

The local climate is temperate, influenced by the moderating effects of nearby San Francisco Bay and the Pacific Ocean to the west, and by the East Bay hills paralleling the eastern shore of this same bay on the east. These physical barriers contribute significantly to the relatively warm, wet winters and cool, dry summers. In 2014, onsite precipitation totaled 34.1 inches (in) (86.6 centimeters [cm]), absolute humidity averaged 8.5 grams/cubic meter (g/m^3), and ambient temperature averaged 58.0 °Fahrenheit (F) (14.4 °Centigrade [C]).

On-site wind patterns change little from one year to the next. The most prevalent wind pattern occurs during fair weather, with daytime westerly winds blowing off the bay, followed by lighter nighttime southeasterly drainage winds off the East Bay hills. The other predominant wind pattern is associated with storm systems passing through the region, which usually occur during the winter months. South-to-southeast winds in advance of each storm are followed by a shift to west or northwest winds after passage of the system.

Vegetation on the Berkeley Lab main site is a mixture of native plants, naturalized exotics, and ornamental species. The site was intensively grazed and farmed for approximately 150 years before Berkeley Lab development began in the 1930s. At the main site, Berkeley Lab manages vegetation in harmony with the local natural succession of native plant communities and maintains the wooded and savanna character of the areas surrounding buildings and roads. Ornamental species are generally restricted to public spaces and courtyards and to areas adjacent to buildings. The site has no known rare, threatened, or endangered plant species.

Wildlife is abundant at the Berkeley Lab main site because it is adjacent to the East Bay Regional Park District and UC open spaces. Wildlife is typical of that found in disturbed (for example, previously grazed) areas of mid-latitude California that feature a Mediterranean climate. More than 120 species of birds, mammals, reptiles, and amphibians are thought to traverse – or exist on the site. The most abundant large mammal is the Colombian black-tailed deer. The Berkeley Lab main site includes protected habitats for spider species, a threatened snake species, and riparian animals.

1.2 Source Description

Berkeley Lab operates facilities subject to the Environmental Protection Agency's (EPA's) National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations where radionuclides are produced, handled, stored, and potentially emitted (EPA 1989a). Figure 1-3 illustrates the Berkeley Lab general site configuration, including locations of buildings where radionuclides are used or produced, and the Lawrence Hall of Science (LHS), which is the location of the maximally exposed individual (MEI). Radionuclides are also used at two offsite locations, Building 977 and Building 978, as shown on Figure 1-2.

Berkeley Lab research programs use a wide variety of radionuclides in gas, liquid, and solid phases, and work with radioactive material may be conducted on laboratory bench tops, in fumehoods, in gloveboxes, and/or under ultra-high vacuum. In addition, short-lived radioactive gases are produced as a by-product of charged-particle accelerator operations in Buildings 6, 56, 71, and 88.

Radiochemical and radiobiological studies performed at Berkeley Lab typically use microcurie to millicurie quantities of a variety of radionuclides. All radioactive material is used in accordance with Berkeley Lab authorizations and permits, which include: 1) the location of radiologically controlled areas (areas to which access is managed to protect individuals from exposure to radiation or radioactive materials), 2) the required handling procedures, and 3) appropriate work enclosures for each project. Table 1-1 identifies buildings at Berkeley Lab where the use or production of unsealed radioactive material was authorized in 2014 and the respective radionuclides at each location. Note that not all authorized radionuclides were used during the year because of the variable nature of Berkeley Lab research projects.

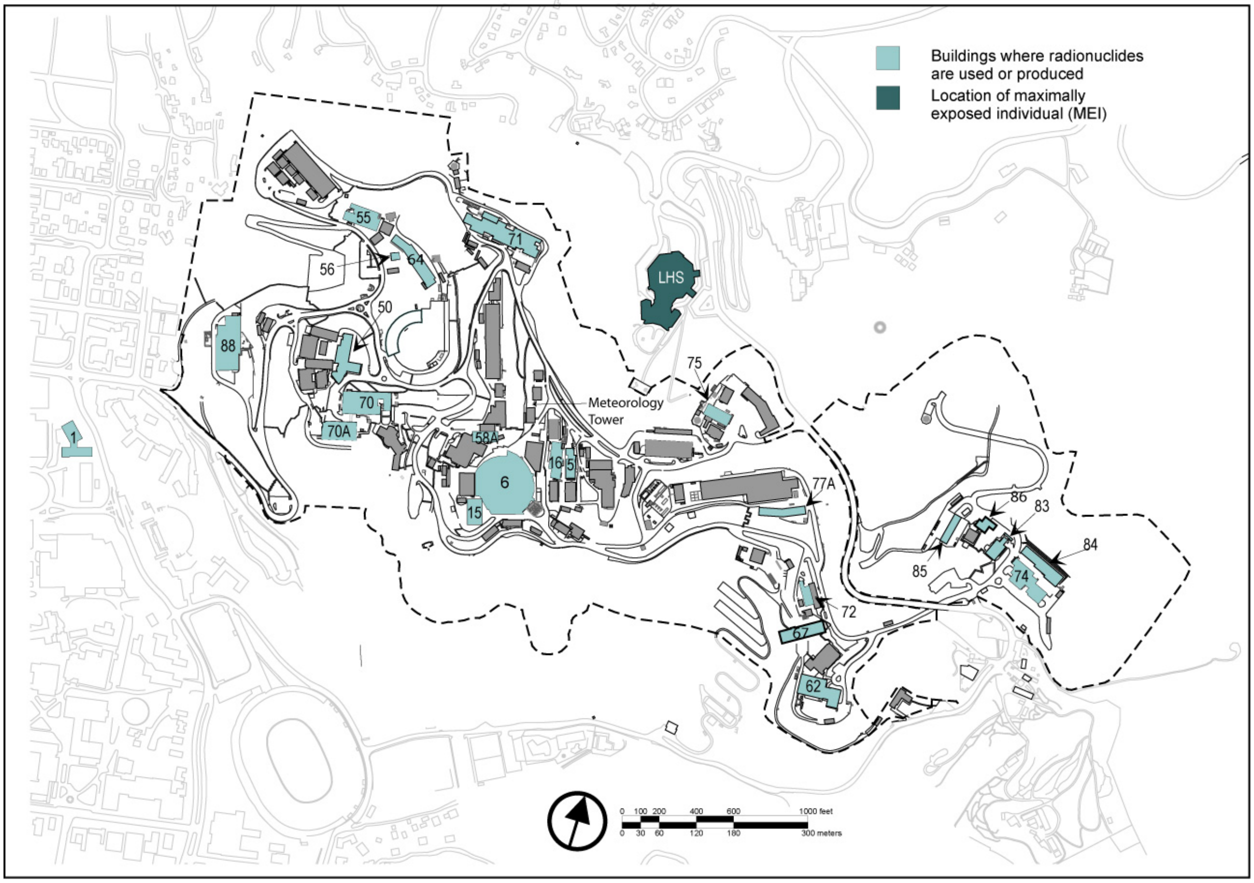

Figure 1-3 Berkeley Lab Buildings Where Radionuclides are Used or Produced

Table 2-1 Buildings Where Unsealed Radionuclide Use or Production was Authorized by Berkeley Lab in 2014

Building	Building Name/Function	Radionuclides Authorized by Berkeley Lab
1	Donner Laboratory	C-14, H-3, P-32, U-238
5	Accelerator and Fusion Research	Activation products[a]
6	Advanced Light Source (ALS)	Activation products [a], Kr-85, P-32, Po-210, Th-229, Th-232, U-238
15	ALS User Support	Alpha-emitting radionuclides, beta-gamma-emitting radionuclides, Th-232, U
16	Accelerator and Fusion Research	Activation products[a]
50 complex	Physics Research	Beta-gamma-emitting radionuclides
55	Radiotracer Development and Imaging Technology	C-11, C-14, Co-55, Co-57, Cr-51, Cu-64, F-17, F-18, Ge-68, H-3, I-123, I-125, I-131, N-13, O-14, O-15, Tc-99m, Tl-201, U-238, Zr-89
56	Biomedical Isotope Facility	C-11, Co-55, Co-57, Cr-51, Cs-137, F-17, F-18, N-13, O-14, O-15, Tc-99m, Zr-89
58A	Accelerator and Fusion Research	Activation products[a]
62	Materials Sciences	H-3, I-125, I-129, Sr-90, U-238
64	Earth Sciences	Cs-137, H-3, Pb-212, Sr-89, Sr-90, Tc-99, Th-228, Th-230, Th-232, Tl-208, U-234, U-235, U-238
67	Materials Sciences	Po-210, U-238
70	Environmental Energy Technology, Nuclear Science, and Earth Sciences Research	Ac-227, Am-240, Am-241, Am-243, Au-198, Ba-133, Be-10, Be-7, Bi-207, Bk-249, C-11, C-14, Cd-109, Cf-249, Cf-250, Cf-251, Cf-252, Cl-36, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Er-165, Er-169, Er-171, Es-253, Es-254, Eu-152, Eu-154, Eu-155, Fe-55, Fe-59, Fm-257, H-3, Ho-166m, Hf-172, Hf-175, Hf-181, Hg-203, Ho-166, Ho-166m, I-125, I-129, Kr-85, Mn-54, Na-22, Nb-95, Ni-57, Ni-63, Ni-65, Np-237, Np-239, P-32, Pa-231, Pa-233, Pb-210, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Ra-228, Re-189, Rh-101, Ru-106, Sb-124, Sb-125, Sc-46, Se-75, Sr-90, Ta-179, Ta-182, Tb-160, Tc-99, Th-228, Th-229, Th-230, Th-232, Tl-204, Tm-170, U-232, U-233, U-234, U-235, U-236, U-238, V-48, Y-90, Zn-65, Zr-88, Zr-95

[a] Produced when materials such as air, water, and metals are activated by neutrons from accelerator or reactor operations; may include ^{41}Ar, ^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{38}Cl, and ^{39}Cl

Table 1-1, continued

Building	Building Name/Function	Radionuclides Authorized by Berkeley Lab
70A	Nuclear, Chemical, and Life Sciences Research	Ac-227, Am-241, Am-243, Ba-133, Bi-207, Bk-249, C-14, Cf-249, Cf-250, Cf-251, Cf-252, Cl-36, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Co-60, Cs-137, Es-253, Es-254, Eu-152, Eu-154, Eu-155, Fe-55, Fe-59, H-3, Ho-166m, I-125, I-129, Ni-63, Ni-65, Np-237, Np-239, Pa-231, Pa-233, Pb-205, Pb-210, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Ra-228, Ru-106, Sr-90, Tc-99, Th-228, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-235, U-236, U-238
71	Lasers and Optical Accelerator Systems Integrated Studies (LOASIS)	Activation products[a]
72	Low-Background Facility; National Center for Electron Microscopy	Ac-227, Am-241, Au-198, Be-10, Be-7, C-11, Cf-249, Cf-252, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Eu-152, Eu-154, Fe-55, Fe-59, Mn-54, Na-22, Np-237, Np-239, P-32, Pa-231, Pa-233, Pu-238, Pu-239, Sb-124, Sc-46, Se-75, U-238, Zn-65
74	Earth Sciences	Ac-227, Am-241, Am-243, Ba-133, Bk-249, C-14, Cf-249, Cf-250, Cf-251, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Cs-137, Es-253, Es-254, Eu-152, Eu-154, Eu-155, H-3, I-125, I-129, Ni-63, Np-237, Np-239, Pa-231, Pa-233, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Sr-90, Tc-99, Th-228, Th-229, Th-230, Th-232, U-232, U-233, U-234, U-235, U-236, U-238
75	Radioanalytical Laboratory	Alpha-emitting radionuclides, beta-gamma-emitting radionuclides
77A	Physics Research	Activation products[a]
83	Life Sciences Research	P-32
84	Life Sciences Research	Ni-63, P-32, S-35
85	Hazardous Waste Handling Facility	Alpha-emitting radionuclides, beta-gamma-emitting radionuclides, Bk-249, C-14, H-3, Np-237, Pu-238, Pu-239, Pu-242, U-233, U-235, U-238
86	Biosciences Research	Cr-51, F-18, I-123, I-125, I-131, Tc-99m, Tl-201, U-238
88	88-Inch Cyclotron	Activation products [a], Ac-227, Am-241, Am-243, As-76, Au-198, Be-10, Be-7, Br-82, C-11, Cf-249, Cf-252, Cm-242, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Co-56, Co-57, Co-58, Co-60, Cr-51, Cs-134, Cs-137, Eu-152, Eu-154, Fe-55, Fe-59, Ir-194m, La-140, Mn-54, Na-22, Na-24, Np-237, Np-239, P-32, Pa-231, Pa-233, Pu-238, Pu-239, Pu-242, Pu-244, Sb-122, Sb-124, Sc-46, Se-75, Th-228, Th-229, Th-232, U-234, U-235, U-236, U-238, Zn-65
977	Berkeley West Biocenter (Potter Street Facility)	C-14, H-3, P-32, S-35
978	Joint BioEnergy Institute (JBEI)	C-14, H-3, P-32, Po-210, S-35, U-238

[a] Produced when materials such as air, water, and metals are activated by neutrons from accelerator or reactor operations; may include ^{41}Ar, ^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{38}Cl, and ^{39}Cl

2

Air Emissions Data

At Berkeley Lab radionuclides may be emitted from point sources such as stacks or other exhaust points (such as vents) on the buildings where radionuclide use or production is authorized (see Table 1-1). Radionuclides could also be uniformly released from an area or emanate from a number of points randomly distributed over an area (referred to as a diffuse source), but in 2014 there were no diffuse sources at Berkeley Lab.

A point source is designated major when, in the absence of all pollution-control equipment, its potential maximum radionuclide emissions can cause a dose greater than 0.1 mrem/yr (0.001 mSv/yr) to the nearest member of the public at an offsite point where there is a residence, school, business, or office. The EPA requires the measurement of emissions from major sources continuously. There are no major sources at Berkeley Lab.

A point source is designated minor when, under the same hypothetical conditions, its potential maximum emissions in the absence of all pollution-control equipment cannot cause a dose greater than 0.1 mrem/yr (0.001 mSv/yr). The EPA requires periodic confirmatory measurements on such sources. In 2014, all Berkeley Lab sources were minor sources of radionuclides. Emissions from minor sources are measured by real-time monitoring, continuous sampling with monthly analysis of the samples, sampling for one month at a time four times a year; or, they are calculated based on quantities received, used, or produced during the year. The approach to measuring radionuclide emissions from Berkeley Lab sources is summarized in Table 2-1, which EPA Region 9 approved in 2005 (Jordan 2005).

Table 2-1 EPA-Approved Radionuclide Emissions Measurement Approach

Potential Dose (mrem/yr)[a]	Category	Requirements
dose ≥ 10.0	Non-compliant	Reduction or relocation of source term and re-evaluation prior to authorization.
10.0 > dose ≥ 1.0	1	• Continuous sampling with weekly collection and analysis AND • Real-time monitoring with alarming telemetry for short-lived ($t_{1/2}$< 100 h) radionuclides resulting in >10% of potential dose to the maximally exposed individual.
1.0 > dose ≥ 0.1	2	• Continuous sampling with monthly collection and analysis OR • Real-time monitoring for short-lived ($t_{1/2}$ < 100 h) radionuclides resulting in >10% of potential dose to the maximally exposed individual.
0.1 > dose ≥ 0.01	3	Periodic sampling 25% of the year.
dose < 0.01	4	Potential dose evaluation before project starts and when annual radionuclide use limits (as authorized by internal Berkeley Lab documents) are revised; no sampling or monitoring required.

[a] 1 mrem = 0.01 mSv

Among the minor sources at Berkeley Lab are a number of stacks (point sources) where the emissions are measured. However, there are significantly more radiologically controlled areas, or group sources, where emissions are calculated. A single building could have all three types of sources: point (measured stacks – typically Category 3), group (calculated emissions – Category 4), and diffuse (calculated wide-area emissions – Category 3 or 4) sources. A tabulation of the different types of Berkeley Lab sources is provided in Table 2-2.

Table 2-2 Measurement Category of Sources

Building	Major Sources		Minor Sources		Total
	Category 1	Category 2	Category 3	Category 4	
1	0	0	0	5	5
6	0	0	0	4	4
15	0	0	0	4	4
16	0	0	0	1	1
50 Complex	0	0	0	7	7
55	0	0	0	16	16
56	0	0	2	0	2
64	0	0	0	2	2
67	0	0	0	2	2
70	0	0	0	19	19
70A	0	0	9	33	42
71	0	0	0	6	6
72	0	0	0	1	1
74	0	0	0	6	6
75 Complex	0	0	1	3	4
77A	0	0	0	1	1
83	0	0	0	2	2
84	0	0	0	9	9
85 Complex	0	0	2	10	12
88	0	0	3	4	7
977	0	0	0	7	7
978	0	0	0	4	4
Total	**0**	**0**	**17**	**146**	**163**

The point and group sources at Berkeley Lab comprise many different radionuclides that were authorized for use or production in 2014 (see Table 1-1); however, not all of those radionuclides were actually received, used, or produced (and thus potentially emitted into the air) during the year because of the variable nature of Berkeley Lab research projects.

Radionuclides that could have been emitted during the year from the Berkeley Lab Main Site are listed in Table 2-3, along with the total activity of each radionuclide from stack and vent air measurements and from calculations.

Table 2-3 Total Activity Potentially Emitted in 2014

Radio-nuclide	Activity (Ci/yr)[a]	Radio-nuclide	Activity (Ci/yr)[a]	Radio-nuclide	Activity (Ci/yr)[a]
F-18	6.65E+00	Pu-240	4.32E-07	Th-229	1.35E-09
C-11	9.79E-03	Am-241	3.00E-07	Fe-59	1.12E-09
C-14	6.00E-03	Be-7	2.70E-07	Th-228	1.00E-09
H-3	9.73E-04	Alpha (Th-232)	2.67E-07	As-76	5.97E-10
N-13	8.47E-04	Co-60	2.60E-07	Br-82	4.13E-10
Cu-64	8.03E-05	P-32	2.50E-07	Na-22	2.06E-10
Tc-99m	5.90E-05	Ta-182	1.77E-07	Ir-194m	1.99E-10
O-15	1.83E-05	Cl-38	1.70E-07	La-140	1.99E-10
Ge-68	1.50E-05	Ra-226	1.25E-07	Sc-46	1.99E-10
Beta (Sr-90)	2.81E-06	Ba-133	1.17E-07	Mn-54	1.11E-10
Cl-39	2.10E-06	Hg-203	1.07E-07	Co-57	1.03E-10
Fe-55	1.00E-06	U-233	8.00E-08	Sb-122	1.03E-10
Ar-41	5.00E-07	I-125	1.29E-08	Th-232	3.13E-11
Na-24	4.82E-07	U-238	2.01E-09		
Au-198	4.82E-07	Kr-85	1.35E-09		
				Total	6.66E+00

[a] 1 Ci = 3.7 × 10^{10} Becquerel (Bq)

2.1 Point Sources: Measured Emissions

In accordance with the EPA-approved approach summarized in Table 2-1, Berkeley Lab measures emissions from stacks or other exhaust points if the potential dose from the sources could exceed 0.01 mrem/yr (0.0001 mSv/yr); these are Category 3 sources (recall that there are no major [Category 1 or 2] sources at Berkeley Lab). Additionally, Berkeley Lab may choose to measure emissions from stacks with less dose impact (Category 4) to ensure that such emissions are well characterized. Thus, stacks where emissions are measured include both Category 3 and Category 4 sources (Table 2-4).

At sampled stacks a representative sample of the exhaust air passes through the appropriate collection medium as follows: silica gel for ^{3}H, sodium hydroxide solution for ^{14}C, activated carbon for ^{125}I, and fiberglass filter for particulate alpha and beta emitting radionuclides. Each medium is changed out after a month and sent to a third-party commercial laboratory for analysis. At sites that are continuously monitored in real time, a sample of the exhaust air is passed through or over detectors that provide a nearly instantaneous measurement of positron-emitting radionuclides (at Buildings 56 and 88) or alpha-emitting radionuclides (at Building 70A). Real-time measurements are recorded and archived.

Many of Berkeley Lab's stacks and vents are equipped with such effluent controls as a filter that collects airborne particulates or gases before they are released to the atmosphere. For example, the measured stacks (point sources) on Building 88 have high-efficiency particulate air (HEPA) filters to prevent small particles from entering the atmosphere. Where effluent controls are in place, samples are collected downstream from the filter except at Building 74 where ventilation restrictions required the placement of the sampler before the HEPA. Table 2-4 details effluent controls on stacks.

Table 2-4 Stacks Where Radionuclide Emissions are Measured

Building	Number of Stacks	Stack Identification	Measurement Category	Effluent Control	Efficiency (%)
55	1	55-128H	4	HEPA [a] TEDA-DAC [b]	> 99 > 75
56	2	56-Accelerator 56-Glovebox	3 3	None [c] None [c]	NA NA
70	1	70-147A	4	HEPA	> 99
70A	9	70A-1121A 70A-1121B 70A-1129P/RT 70A-1129H 70A-2211 70A-2217 70A-2223 70A-2229A 70A-2229B	3 3 3 3 3 3 3 3 3	None None HEPA HEPA None None None None None	NA NA > 99 > 99 NA NA NA NA NA
74	1	74-116	4	HEPA	> 99
75	1	75-127H	3	HEPA	> 99
85	2	85-Fumehood 85-Glovebox	3 3	HEPA HEPA	> 99 > 99
88	3	88-135H 88-Cave0 88-RT	3 3 3	HEPA HEPA HEPA	> 99 > 99 > 99

[a] High-efficiency particulate air filter
[b] Triethylene-diamine-doped activated carbon trap
[c] Radionuclides emitted from Building 56 stacks are short-lived, gaseous activation products for which emission control is impractical

2.2 Group Sources: Calculated Emissions

In accordance with the EPA-approved approach (Table 2-1), Berkeley Lab calculates emissions from stacks or other exhaust points if the potential dose from the sources is less than 0.01 mrem/yr (0.0001 mSv/yr). These Category 4 sources (typically radiologically controlled areas where small amounts of radionuclides are authorized for use) are grouped by building, as shown in Table 2-5, to simplify reporting (DOE 1994). In Table 2-5, multiple lines for a location indicates the site has effluent stacks with HEPA controls and stacks without. The amount of each radionuclide emitted is calculated by multiplying the entire quantity of that radionuclide received, used, or produced during the year by the appropriate EPA-specified release factor based on the radionuclide’s physical state, as provided in 40 Code of Federal Regulations (CFR) Part 61, Appendix D. This method provides a conservative, upper-bound estimate of the annual emissions.

Table 2-5 Sources for Which Radionuclide Emissions are Calculated

Building	Number of Radiologically Controlled Areas	Emissions Control	Efficiency (%)
1	5	None	NA[a]
6	4	None	NA
15	4	None	NA
16	1	None	NA
50 complex	7	None	NA
55	15	HEPA [b] None	> 99 NA
64	2	None	NA
67	2	None	NA
70	18	HEPA None	> 99 NA
70A	33	HEPA None	> 99 NA
71	6	None	NA
72	1	None	NA
74	5	HEPA None	> 99 NA
75 Complex	3	HEPA None	> 99 NA
77A	1	None	NA
83	2	None	NA
84	9	None	NA
85 Complex	10	HEPA None	> 99 NA
88	4	HEPA	> 99
977	7	None	NA
978	4	None	NA

[a] Not applicable
[b] High-efficiency particulate air filter

Emissions of radionuclides received during the year are typically calculated with the assumption that during the year those radionuclides are used in areas where stacks or other exhaust points are not sampled or otherwise monitored. Some received radionuclides may be emitted through sampled or monitored stacks, thus reported emissions may be higher than actual emissions because they are accounted for as both calculated and measured emissions. For group sources there typically are no effluent controls, as emissions from these sources are very small.

2.3 Nonpoint Sources: Diffuse Emissions

There were no diffuse emissions at Berkeley Lab in 2014.

3
Dose Assessment

3.1 Dose Model

To comply with NESHAP regulations and DOE guidance, the EPA-approved atmospheric dispersion and radiation dose calculation computer code, CAP88-PC, Version 4.0, was used to calculate the doses at various distances and from various release points (EPA 2006). For Buildings 1, 977, and 978 – where the nearest member of the public was much less than 328 ft (100 m) from the source – the EPA-approved dose model COMPLY was used to calculate MEI dose (the highest dose to any member of the public at any offsite point where there is a residence, school, business, or office), and CAP88-PC was used for doses at all other distances from the building. Doses to members of the public nearest each building were compared, and the location where the dose was greatest was determined to be the MEI.

Doses to the MEI from individual building emissions on the main site and for nearby Building 1 were calculated and the individual doses were then summed. (Building 1 is located on the adjacent UC Berkeley campus and is within walking distance of the main Berkeley Lab site, as shown on Figure 1-3.)

For Buildings 977 and 978, doses were evaluated for each building individually, and a separate MEI was determined for each building. Buildings 977 and 978 are located about 3 mi (5 km) west and southwest, respectively, of the main site, as shown on Figure 1-2.

3.2 Input Parameters

Input parameters to CAP88-PC and COMPLY include the emissions discussed in Section 2, and building-specific and common parameters discussed below. To estimate doses, CAP88-PC, Version 4.0, provides a library of 825 radionuclides, which includes data for all of the radionuclides received, used, or produced during the year.

Previously, for very small quantities of radionuclides (less than 1×10^{-10} Ci [3.7 bequerel, Bq]), CAP88-PC, Version 3 was unable to produce a numerical radiological dose and would provide zero. CAP88-PC, Version 4, is able to calculate doses for activities less than 1×10^{-10} Ci (3.7 Bq). In 2014, several radionuclides were used in quantities less than 1×10^{-10} Ci (3.7 Bq) and were tallied in order to provide a calculated dose to the MEI. These radionuclides were shown to have no measurable contribution to the MEI dose, thus verifying the assumption that had been made in previous years.

When calculating doses from particulate alpha and beta emitting radionuclides, Berkeley Lab assigns gross alpha and gross beta measurements to the high-hazard alpha-emitting radionuclide ^{232}Th and the high-hazard beta-emitting radionuclide ^{90}Sr, respectively. The use of the high-hazard radionuclides ^{232}Th and ^{90}Sr to represent alpha and beta emissions provides an upper-bound estimate of the dose.

3.2.1 Building-Specific Parameters

For dose assessment, certain Berkeley Lab buildings can be combined because of their proximity to each other and the similarity in the types of operations that are performed in these buildings (DOE 1994). For combined buildings and buildings with many unsampled stacks and vents, average stack height along with assumed stack diameter (0.3 ft [0.1 m]), exit velocity (0 ft/s [0 m/s]), and receptor distance (from nearest edge of building) values are typically used (Table 3-1). These input values provide an upper-bound estimate of dose and ensure that stack and vent emissions are not underestimated.

For Buildings 56, 75, and 85, where some radionuclide emissions can be correlated to specific stacks (such as glovebox or fumehood stacks), the actual stack diameter and exit velocity are used and modeled separately. The input parameters that vary with building are shown in Table 3-1.

For the Building 50 complex, 58A, and 77A, authorized radionuclides are in the form of activated materials, which are fixed and not readily dispersed into the air. Because airborne radionuclides are unlikely to be released from these buildings, no emissions were modeled.

Table 3-1 Building-Specific Input Parameters

Building Number	Stack Height (m)[a]	Stack Diameter (m)	Assumed /Measured Exit Velocity (m/s)	Nearest Member of Public	MEI Location [b]	Farm Location [c]
1	18	0.1	0	10 m ESE	990 m ENE	4200 m N
5/6/15/16	9	0.1	0	350 m NNE	370 m NNE	3200 m N
55/56/64						
Accelerator stack	16	0.3	3.70	250 m NNW	460 m E	3200 m N
Glovebox stack	16	0.46	2.40	250 m NNW	460 m E	3200 m N
General stacks	12	0.1	0	250 m NNW	460 m E	3200 m N
62/67/72	3	0.1	0	230 m SSW	500 m NW	3200 m N
70/70A	16	0.1	0	270 m WSW	530 m ENE	3200 m N
71	13	0.1	0	190 m NNW	310 m ESE	3200 m N
74/83/84/86	7	0.1	0	160 m SSE	690 m WNW	3200 m N
75	7.4	0.35	8.03	110 m NW	110 m NW	3200 m N
85						
Glovebox stack	16	0.23	6.77	210 m SSE	570 m WNW	3200 m N
Fumehood stack	16	0.46	4.32	210 m SSE	570 m WNW	3200 m N
General stacks	16	0.1	0	210 m SSE	570 m WNW	3200 m N
88	13	0.1	0	110 m W	690 m ENE	3200 m N
977	16	0.1	0	30 m N	30 m N	8200 m N
978	28	0.26	0	19 m E	19 m E	8200 m N

[a] 1 m = 3.281 ft

[b] For main site buildings, the MEI is at the Lawrence Hall of Science; for offsite buildings, the MEI is in each offsite building

[c] Approximate distance to Wildcat Canyon Regional Preserve where cattle graze

For Buildings 977 and 978, which are off the main site and are shared by Berkeley Lab employees and members of the public, the distance to the MEI is the shortest distance from the release point on the building roof to the location of the nearest member of the public in the building (measured along the building surfaces). This is the distance calculation required by the COMPLY software (EPA 1989b).

3.2.2 Common Parameters

The input parameters that are common among Berkeley Lab sources include meteorological data and agricultural data. Meteorological data was compiled from onsite data for 2014. Berkeley Lab collects this data from an 86-ft (26-m) tower centrally located on the main site (see Figure 1-3). Site-specific values for annual precipitation (34.1 in. [86.6 cm]), average ambient temperature (58.0 °F [14.4 °C]), and average absolute humidity (8.5 g/m^3) were used. The default value for lid (mixing) height, 3300 ft (1000 m), was chosen. The 2014 wind data are provided in Appendix A.

Agricultural data were obtained from the California Department of Food and Agriculture and the urban scenario was chosen (Wahl 2004). The values include the following.

- Vegetables, fraction home-produced: 0.076
- Vegetables, fraction from assessment area: 0.924
- Milk, fraction from assessment area: 1
- Meat, fraction home-produced: 0.008
- Meat, fraction from assessment area: 0.992
- Beef cattle density: 1.9 per square kilometer (km^2)
- Milk cattle density: 4.0 per km^2
- Land fraction cultivated for vegetable crops: 0.046

3.3 Compliance Assessment

3.3.1 MEI Dose and Location

Doses from Berkeley Lab's airborne emissions are well below the 10 mrem/yr (0.1 mSv/yr) NESHAP dose standard. As shown in Table 3-2, the sum of calculated doses from all sources at Berkeley Lab main site in 2014 was 2.7×10^{-2} mrem/yr (2.7×10^{-4} mSv/yr) to the MEI (the member of the public who potentially received the highest dose at any offsite point where there is a residence, school, business, or office). The location of this hypothetical person is the UC Lawrence Hall of Science, about 1500 ft (460 m) east of Buildings 55 and 56. The calculated doses from sources at the offsite Buildings 977 and 978 to the nearest member of the public working in the same building (the building-specific MEI) were 1.6×10^{-4} mrem/yr (1.6×10^{-6} mSv/yr) and 1.3×10^{-3} mrem/yr (1.3×10^{-5} mSv/yr), respectively.

Although no one actually lives at the MEI locations, the EPA-approved software calculates the dose assuming a person resides there 24 hours a day for the entire year, eats meat and vegetables grown nearby (see the agricultural parameters in Section 3.2.2), and drinks water from local wells presumed to be contaminated with deposited airborne radionuclides. Thus the calculated dose to this hypothetical person, the MEI, is greater than the dose to an actual member of the public visiting the Hall of Science or working in Buildings 977 or 978.

Table 3-2 Dose Assessment Results

Building	Primary Radionuclides Contributing to MEI Dose[a]	Dose to MEI (mrem/yr)[b]	Percent of Total Dose (%)
1	None	4.3E-8	< 0.1
5/6/15/16	None	1.79E-6	<0.1
55/56/64	F-18	2.50E-2	93.0
62/67/72	None	0	< 0.1
70/70A	None	1.34E-4	0.5
71	None	1.97E-7	< 0.1
74/83/84/86	None	7.94E-6	< 0.1
75	C-14	1.00E-3	3.74
85	Gross alpha	6.71E-4	2.0
88	None	7.02E-5	0.3
Total (Main Site)		2.7E-2	100
977	P-32	1.6E-4	100
978	U-238	1.3E-3	100

[a] Radionuclides that contribute more than 1% of the potential dose to the MEI from this source
[b] Dose from all radionuclides emitted; 1 mrem = 0.01 mSv

Emissions of ^{18}F from Building 56 stacks account for about 93% of the dose to the Berkeley Lab main site MEI. Reported annual ^{18}F emissions from Building 56 stacks are likely to be higher than actual emissions because false-positive results occur when ^{18}F adsorbs onto the real-time detectors and continues to decay there. These false positive measurements are included in the calculation of annual ^{18}F emissions. As a result, the calculated dose represents an upper-bound estimate of dose from ^{18}F. Even with this upper-bound estimate, the dose to the MEI from ^{18}F is very low – only about 0.3% of the EPA limit of 10 mrem/yr (0.1 mSv/yr). Previous years' emissions sorted by location from the time period 2010 to 2014 are shown in Figure 3-1. A small increase in dose to the MEI was noted in 2014; this dose was attributable to an increase in emissions from a Building 56 stack. The cause of the increase was a failure in emissions abatement equipment that acts as a scrubber on the accelerator exhaust for short-lived radionuclides. This equipment allows radionuclides to decay in a controlled environment prior to being quantified by radiation monitoring equipment and then emitted to the environment. The equipment issue has since been resolved. This increase does not qualify as an unplanned emission per 40 CFR part 61, subpart H.

The CAP88-PC and COMPLY codes were validated by performing sample assessments. The output of each sample assessment was compared to output provided in the users' guides (EPA 2014, EPA 1989b). The two outputs are identical, indicating that the code performed as intended.

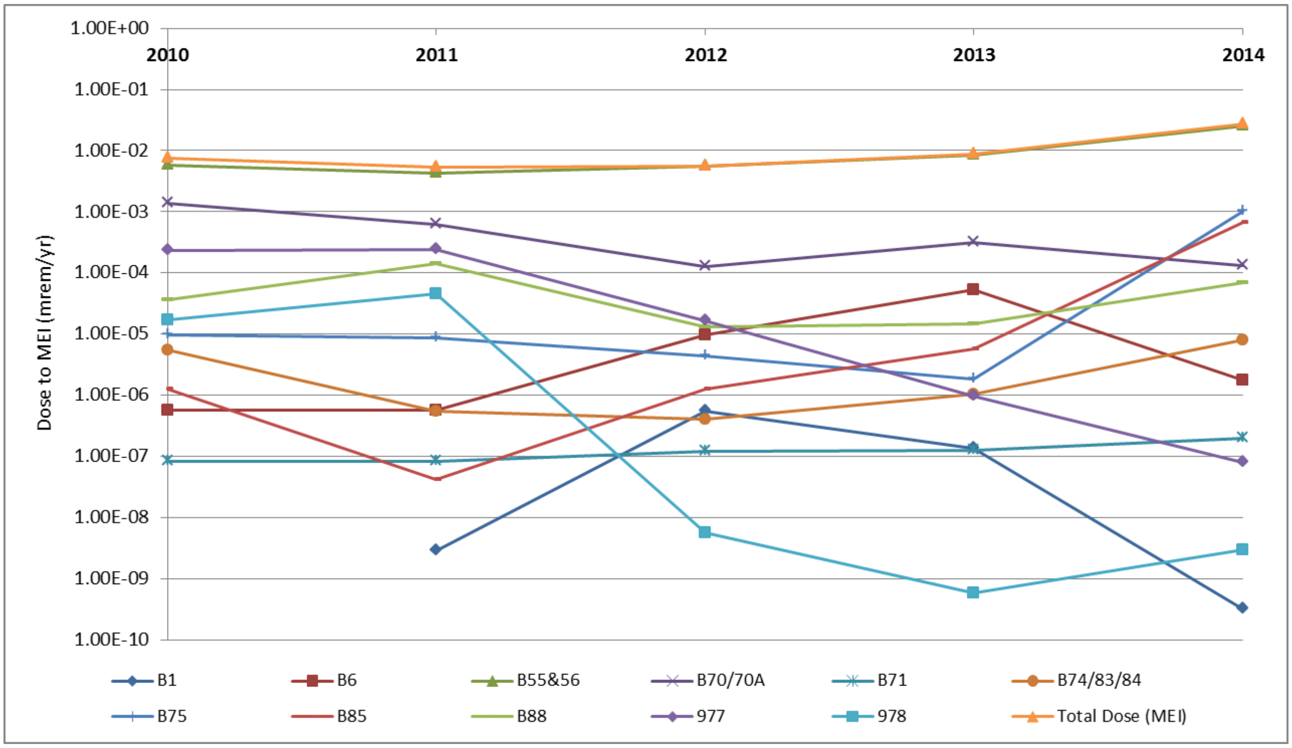

Figure 3-1 Berkeley Lab Total Dose to MEI by Location (2010 to 2014)

Certification

As required by 40 CFR 61.94(b)(9), the following declaration must be signed and dated by Berkeley Lab officials in charge:

"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)."

Certified By:

Signature on file — Date: 6/18/2015

James G. Floyd, Division Director
Environment / Health / Safety Division
Lawrence Berkeley National Laboratory

Signature on file — Date: 6/25/2015

Mary Gross, ES&H Division Director
Lawrence Berkeley Site Office
Department of Energy

4

Additional Information

4.1 Additions or Modifications

There was no facility construction or modification (fabrication, erection, or installation) in 2014 relevant to the NESHAP regulation. Other changes that could affect radionuclide emissions noted in this report include:

- Cessation of research work with radionuclides at Buildings 5 & 16 and the beginning of a planned demolition that is scheduled for calendar year 2015 that will likely create a diffuse source of radioactive material.

4.2 Unplanned Releases

There were no unplanned releases in 2014 from Berkeley Lab operations.

4.3 Diffuse Emissions

There were no diffuse emissions in 2014 from Berkeley Lab operations.

5
Supplemental Information

5.1 Collective Dose Estimate

Collective population dose is calculated as the average radiation dose to a person in a specified area, multiplied by the number of people in that area. In accordance with DOE and EPA guidance documents, all radionuclides potentially emitted from the main Berkeley Lab site in 2014 (shown in Table 2-3) were assumed to be released from a hypothetical, centrally located stack that is 52 ft (16 m) high, is 1 ft (0.3 m) in diameter, and has an exit velocity of 13.5 feet/second (ft/s) (4.1 meters/second [m/s]) (Wahl 2003). Radionuclides potentially emitted from Building 977 were assumed to be released from the building stack, which is 52 ft (16 m) high, is assumed to be 0.3 ft (0.1 m) in diameter, and has an assumed exit velocity of 0 ft/s (0 m/s). Radionuclides potentially emitted from Building 978 were assumed to be released from the building stack, which is 92 ft (28 m) high, is 0.85 ft (0.26 m) in diameter, and has an assumed exit velocity of 0 ft/s (0 m/s).

The total daytime population within 50 mi (80 km) of the main Berkeley Lab site is approximately 7,253,038 (Bright 2011).[1] The same population was assumed to be appropriate for Buildings 977 and 978, since they are relatively close to (within 3 mi [5 km] of) the main Berkeley Lab site. The population file is provided in Appendix B, which was updated in 2012 to incorporate 2010 U.S. census data (Rose 2012). Daytime population is greater than nighttime population in the area surrounding Berkeley Lab, and when doses to both daytime and nighttime populations were compared, daytime population files yielded higher doses, so daytime population was the basis for 2014 collective dose estimates.

The estimated collective dose to persons living within 50 mi (80 km) of the main Berkeley Lab site is 3.2×10^{-1} person-rem (3.2×10^{-3} person-Sv) attributable to Berkeley Lab airborne emissions in 2014. The collective doses from Building 977 and 978 are 3.9×10^{-6} person-rem (3.9×10^{-8} person-Sv) and 4.0×10^{-6} person-rem (4.0×10^{-8} person-Sv), respectively.

5.2 40 CFR 61 Subparts Q and T

Subparts Q and T of 40 CFR 61 are not applicable because Berkeley Lab does not operate a storage and disposal facility for radium-containing material or uranium mill tailings.

[1] Population data were obtained from the LandScan (2010)™ High Resolution Global Population Data Set copyrighted by UT-Battelle, LLC, operator of Oak Ridge National Laboratory under Contract No. DE-AC05-00OR22725 with the United States Department of Energy. The United States government has certain rights in this data set. Neither UT-Battelle, LLC, nor the United States Department of Energy, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of the data set.

5.3 Radon Emissions

Berkeley Lab does not process, manage, or possess ^{232}U or ^{232}Th in quantities that could produce ^{220}Rn emissions having an impact $\geq$ 0.1 mrem/yr (0.001 mSv/yr) or $\geq$ 10% of the nonradon dose to the public. Berkeley Lab does not maintain nondisposal or nonstorage sources of ^{222}Rn emissions in quantities having an impact $\geq$ 0.1 mrem/yr (0.001 mSv/yr) or $\geq$ 10% of the nonradon dose to the public.

5.4 Facility Compliance

In 2014, no release points produced emissions having an impact $\geq$ 0.1 mrem/yr (0.001 mSv/yr) and no sources were subject to continuous monitoring requirements. Periodic confirmatory measurements were conducted in accordance with the EPA-approved measurement approach (Table 2-1).

6

References

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DOE 1994: U.S. Department of Energy, "Calendar Year 1993 Radionuclide Air Emissions Annual Reports for DOE Sites," memo to DOE site offices providing guidance for report preparation (March 22, 1994).

EPA 1989a: U.S. Environmental Protection Agency, National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities, 40 CFR Part 61, Subpart H (1989, as amended).

EPA 1989b: U.S. Environmental Protection Agency, *Users Guide for the COMPLY Code,* EPA 520/1-89/2003 (October 1989).

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MTC/ABAG 2010: Metropolitan Transportation Commission/Association of Bay Area Governments, *Bay Area Census,* 2010 census data website, http://www.bayareacensus.ca.gov/cities/cities.htm (accessed March 30, 2014).

Rose 2012: Rose, A. N., Oak Ridge National Laboratory, letter to L. Wahl, Lawrence Berkeley National Laboratory, describing population files prepared for use with CAP88-PC.

Wahl 2003: Wahl, L., "Annual Calculation of Collective Dose from Airborne Radionuclides," memo ES-03-037 to file documenting stack parameters for collective dose calculations (October 9, 2003).

Wahl 2004: Wahl, L., "Agricultural Data Used in CAP88-PC," memo ES-05-003 to file documenting source of agricultural values used for collective dose calculations (October 26, 2004).

Appendix A

Meteorological Data

Wind Direction	Stability Category	2014 Average Wind Frequency at Given Speed					
		1-3 knots	4-6 knots	7-10 knots	11-16 knots	17- 21 knots	> 21 knots
N	A	0.00034	0.00000	0.00000	0.00000	0.00000	0.00000
NNE	A	0.00057	0.00023	0.00000	0.00000	0.00000	0.00000
NE	A	0.00126	0.00069	0.00000	0.00000	0.00000	0.00000
ENE	A	0.00080	0.00069	0.00000	0.00000	0.00000	0.00000
E	A	0.00080	0.00069	0.00000	0.00000	0.00000	0.00000
ESE	A	0.00023	0.00046	0.00000	0.00000	0.00000	0.00000
SE	A	0.00034	0.00023	0.00000	0.00000	0.00000	0.00000
SSE	A	0.00057	0.00011	0.00000	0.00000	0.00000	0.00000
S	A	0.00034	0.00023	0.00000	0.00000	0.00000	0.00000
SSW	A	0.00023	0.00023	0.00000	0.00000	0.00000	0.00000
SW	A	0.00080	0.00000	0.00000	0.00000	0.00000	0.00000
WSW	A	0.00069	0.00011	0.00000	0.00000	0.00000	0.00000
W	A	0.00034	0.00011	0.00000	0.00000	0.00000	0.00000
WNW	A	0.00080	0.00011	0.00000	0.00000	0.00000	0.00000
NW	A	0.00023	0.00034	0.00000	0.00000	0.00000	0.00000
NNW	A	0.00046	0.00057	0.00000	0.00000	0.00000	0.00000
N	B	0.00011	0.00023	0.00023	0.00000	0.00000	0.00000
NNE	B	0.00057	0.00034	0.00000	0.00000	0.00000	0.00000
NE	B	0.00046	0.00069	0.00000	0.00000	0.00000	0.00000
ENE	B	0.00057	0.00057	0.00091	0.00000	0.00000	0.00000
E	B	0.00046	0.00114	0.00034	0.00000	0.00000	0.00000

Wind Direction	Stability Category	2014 Average Wind Frequency at Given Speed					
		1-3 knots	4-6 knots	7-10 knots	11-16 knots	17- 21 knots	> 21 knots
ESE	B	0.00011	0.00023	0.00000	0.00000	0.00000	0.00000
SE	B	0.00011	0.00000	0.00011	0.00000	0.00000	0.00000
SSE	B	0.00046	0.00011	0.00000	0.00000	0.00000	0.00000
S	B	0.00194	0.00126	0.00034	0.00000	0.00000	0.00000
SSW	B	0.00217	0.00240	0.00034	0.00000	0.00000	0.00000
SW	B	0.00160	0.00137	0.00057	0.00000	0.00000	0.00000
WSW	B	0.00137	0.00091	0.00069	0.00000	0.00000	0.00000
W	B	0.00080	0.00023	0.00011	0.00000	0.00000	0.00000
WNW	B	0.00057	0.00057	0.00011	0.00000	0.00000	0.00000
NW	B	0.00011	0.00080	0.00023	0.00000	0.00000	0.00000
NNW	B	0.00057	0.00149	0.00000	0.00000	0.00000	0.00000
N	C	0.00034	0.00034	0.00023	0.00000	0.00000	0.00000
NNE	C	0.00034	0.00034	0.00000	0.00000	0.00000	0.00000
NE	C	0.00034	0.00046	0.00011	0.00046	0.00000	0.00000
ENE	C	0.00057	0.00069	0.00091	0.00103	0.00000	0.00000
E	C	0.00023	0.00034	0.00114	0.00057	0.00000	0.00000
ESE	C	0.00103	0.00114	0.00080	0.00034	0.00000	0.00000
SE	C	0.00149	0.00194	0.00206	0.00126	0.00000	0.00000
SSE	C	0.00548	0.00788	0.00274	0.00091	0.00000	0.00000
S	C	0.00788	0.00400	0.00000	0.00000	0.00000	0.00000
SSW	C	0.00765	0.00274	0.00000	0.00000	0.00000	0.00000
SW	C	0.00971	0.00663	0.00034	0.00000	0.00000	0.00000
WSW	C	0.01394	0.01805	0.00434	0.00000	0.00000	0.00000
W	C	0.01839	0.03153	0.01931	0.00091	0.00000	0.00000
WNW	C	0.00423	0.00731	0.00103	0.00000	0.00000	0.00000

Wind Direction	Stability Category	2014 Average Wind Frequency at Given Speed					
		1-3 knots	4-6 knots	7-10 knots	11-16 knots	17- 21 knots	> 21 knots
NW	C	0.00126	0.00160	0.00023	0.00000	0.00000	0.00000
NNW	C	0.00080	0.00103	0.00000	0.00000	0.00000	0.00000
N	D	0.00480	0.00708	0.00354	0.00011	0.00000	0.00000
NNE	D	0.00114	0.00137	0.00137	0.00023	0.00000	0.00000
NE	D	0.00114	0.00057	0.00228	0.00103	0.00023	0.00000
ENE	D	0.00080	0.00149	0.00377	0.00228	0.00103	0.00000
E	D	0.00194	0.00057	0.00354	0.00263	0.00046	0.00011
ESE	D	0.01394	0.01028	0.00777	0.00137	0.00000	0.00000
SE	D	0.02102	0.01748	0.01462	0.00617	0.00011	0.00000
SSE	D	0.01165	0.00651	0.00537	0.00137	0.00046	0.00023
S	D	0.00366	0.00000	0.00011	0.00000	0.00000	0.00000
SSW	D	0.00434	0.00000	0.00000	0.00000	0.00000	0.00000
SW	D	0.00663	0.00034	0.00034	0.00000	0.00000	0.00000
WSW	D	0.01302	0.00457	0.00137	0.00000	0.00000	0.00000
W	D	0.04398	0.02022	0.01565	0.00091	0.00000	0.00000
WNW	D	0.04866	0.03564	0.01245	0.00457	0.00000	0.00000
NW	D	0.00834	0.00331	0.00011	0.00000	0.00000	0.00000
NNW	D	0.00800	0.00137	0.00011	0.00000	0.00000	0.00000
N	E	0.00605	0.00274	0.00046	0.00023	0.00000	0.00000
NNE	E	0.00354	0.00103	0.00183	0.00000	0.00000	0.00000
NE	E	0.00080	0.00023	0.00057	0.00000	0.00000	0.00000
ENE	E	0.00171	0.00023	0.00034	0.00000	0.00000	0.00000
E	E	0.00446	0.00046	0.00046	0.00000	0.00000	0.00000
ESE	E	0.01873	0.00274	0.00023	0.00000	0.00000	0.00000
SE	E	0.02216	0.00594	0.00011	0.00000	0.00000	0.00000

Wind Direction	Stability Category	2014 Average Wind Frequency at Given Speed					
		1-3 knots	4-6 knots	7-10 knots	11-16 knots	17- 21 knots	> 21 knots
SSE	E	0.01154	0.00377	0.00011	0.00000	0.00000	0.00000
S	E	0.00297	0.00000	0.00000	0.00000	0.00000	0.00000
SSW	E	0.00320	0.00011	0.00000	0.00000	0.00000	0.00000
SW	E	0.00377	0.00080	0.00000	0.00000	0.00000	0.00000
WSW	E	0.00457	0.00640	0.00023	0.00000	0.00000	0.00000
W	E	0.00834	0.00697	0.00000	0.00000	0.00000	0.00000
WNW	E	0.01919	0.00240	0.00114	0.00000	0.00000	0.00000
NW	E	0.01268	0.00080	0.00000	0.00000	0.00000	0.00000
NNW	E	0.00834	0.00274	0.00000	0.00000	0.00000	0.00000
N	F	0.01257	0.00240	0.00034	0.00000	0.00000	0.00000
NNE	F	0.00320	0.00137	0.00000	0.00000	0.00000	0.00000
NE	F	0.00194	0.00171	0.00011	0.00000	0.00000	0.00000
ENE	F	0.00331	0.00263	0.00046	0.00000	0.00000	0.00000
E	F	0.00880	0.00297	0.00011	0.00000	0.00000	0.00000
ESE	F	0.01485	0.00149	0.00000	0.00000	0.00000	0.00000
SE	F	0.01359	0.00114	0.00000	0.00000	0.00000	0.00000
SSE	F	0.01119	0.00548	0.00011	0.00000	0.00000	0.00000
S	F	0.00754	0.00366	0.00000	0.00000	0.00000	0.00000
SSW	F	0.00708	0.00503	0.00000	0.00000	0.00000	0.00000
SW	F	0.00834	0.00525	0.00000	0.00000	0.00000	0.00000
WSW	F	0.00651	0.00834	0.00000	0.00000	0.00000	0.00000
W	F	0.00880	0.00343	0.00000	0.00000	0.00000	0.00000
WNW	F	0.01085	0.00000	0.00000	0.00000	0.00000	0.00000
NW	F	0.01005	0.00149	0.00000	0.00000	0.00000	0.00000
NNW	F	0.00537	0.00331	0.00011	0.00000	0.00000	0.00000

Appendix B

Population Data

Direction	Daytime Population at Given Distance from Center of Berkeley Lab												
	0.5 km	1 km	2 km	3 km	4 km	5 km	10 km	20 km	30 km	40 km	50 km	60 km	80 km
N	567	81	130	6	0	0	635	23847	82827	25150	69500	25407	2057
NNW	288	177	646	706	421	360	2221	44047	0	1505	15306	16894	146651
NW	2117	470	509	1724	2628	2432	27072	53782	759	47974	12010	63143	133736
WNW	1035	1272	2374	3707	5548	9824	11906	14989	104906	27867	1109	2206	213
W	588	5841	10215	3236	5045	8929	2212	5050	41590	1468	208	0	0
WSW	26	6068	30481	14780	3896	12215	16	186522	157613	0	0	0	0
SW	3	10876	9187	4977	5040	6451	27269	415153	336243	49559	7	0	0
SSW	0	2015	3578	8427	4124	9726	100986	14541	53596	135496	20513	2502	135
S	0	255	1477	3381	4895	8535	67419	65855	0	163234	234910	69451	3269
SSE	13	72	1687	818	1118	2344	35125	158180	165619	137362	154068	450963	1208150
SE	4	0	67	485	420	930	4715	10557	63937	59845	76387	11716	54799
ESE	10	81	0	10	12	0	3805	12731	81261	102471	75005	33070	55123
E	73	429	0	4	3	19	9152	72495	14988	564	41842	12620	52114
ENE	253	334	0	1	171	638	3588	92833	108690	68712	87238	10380	14795
NE	507	15	8	0	1	693	806	45538	34441	4250	112	1666	2487
NNE	525	425	0	0	0	0	15	5489	31120	17416	94187	78096	46520